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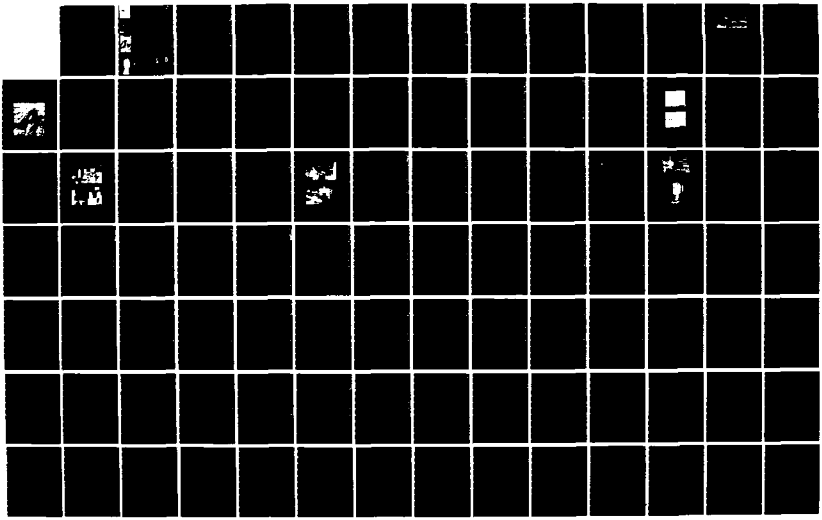

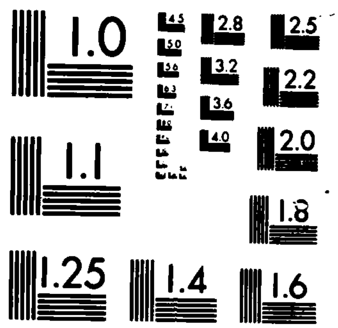

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A STATIC ANALYSIS OF ERRORS IN TRANSDUCER CALIBRATION TECHNIQUES USED FOR BLAST PHENOMENA TESTS

by

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Strain gage transducers are commonly used in the formation of measurement circuits for recording different physical phenomena such as acceleration, displacement, pressure, etc. One method of rating used in these circuits is the shunt resistor calibration technique, which is considered both satisfactory and reliable. A mathematical model representing the static measurement circuit is used to study the effect of major parameters on the calibration

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procedure. Three parameters are considered: the length of the cable which connects the transducer to the rest of the measurement circuit elements, the nonlinear characteristic of the transducer, and the balanced potentiometer setting. The main advantage gained from this investigation is the improvement in measurement accuracy.

Keywords: Army Corps of Engineers; Waterways Experiment Station; statistical analysis; static electrical response; strain gage bridge units.

PREFACE

The analysis in this report was conducted by Instrumentation Services Division (ISD), US Army Engineer Waterways Experiment Station (WES), during the period November 1983 through January 1984 for the Structures Laboratory, WES.

The general body of this report is divided into three major parts: the reasons for conducting the analysis; the techniques adopted to perform the analysis along with the results; and the conclusions and recommendations following the study.

The following employees who contributed valuable assistance in one or more parts of this report were Messrs. C. Cox, G. Downing, J. Ferguson, N. Lavecchia, F. Leake, L. Sadler, D. Rickman, G. Smith, and Ms. S. McDonald. The work was conducted under the direct supervision of Mr. George P. Bonner, Chief, ISD.

Commanders and Directors of WES during this study and the preparation of this report were COL Tilford C. Creel, CE, and COL Robert C. Lee, CE. COL Allen F. Grum, USA, was Director of WES during the publication of this report. Technical Directors were Mr. Fred R. Brown and Dr. Robert W. Whalin.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
inches per second	0.0254	metres per second
pounds (force) per square inch	6894.757	pascals

A STATIC ANALYSIS OF ERRORS IN TRANSDUCER CALIBRATION TECHNIQUES USED FOR BLAST PHENOMENA TESTS

PART I: INTRODUCTION

Physical Phenomena to be Measured

1. The Waterways Experiment Station (WES) has been involved in military research programs to investigate blast phenomena for more than three decades. Measurements of many different parameters associated with blast phenomena have been necessary in order to supply the required information to the WES researchers.

2. While these research programs have addressed many diverse problems and goals, the categories of parameters to be measured during the test phase of the programs are not so numerous. Parameters most commonly measured in blast-phenomena-type tests are:

- a. Acceleration.
- b. Velocity.
- c. Displacement.
- d. Airblast pressure.
- e. Water-shock pressure.
- f. Strain.
- g. Time of arrival.

Types of Transducers Used in Blast Phenomena Measurement

3. Transducers used to measure different parameters in the blast phenomena investigations are as diverse in mechanical configuration as the physical parameters are in variety. In the majority of cases the transducers are used to convert the physical parameters into an electrical signal that bears a known and predictable relationship to such physical input. Figure 1 shows some of the types of transducers used in blast phenomena testing. A more complete listing of transducer types is noted below:

- a. Metal strain gage.
- b. Piezoresistive strain gage.

_c_. Linear variable differential transformers.

_d_. E-core transformer.

_e_. Magnetized structures and pickup coils.

_f_. Piezolectric.

_g_. Capacitive.

_h_. Potentiometer.

_i_. Photosensitive.

_j_. Ionization.

4. Strain-gage bridge transducers constitute by far the largest group of transducers used by WES in blast phenomena measurements. Fundamentally, the small size and high frequency response of strain-gage elements have made them especially well adapted for blast phenomena measurements. Because of the predominant use of strain-gage transducers in WES blast phenomena measurement, and limitations of time and funding, this report addresses only a static analysis of strain-gage bridge circuits.

Blast Phenomena Measurement Peculiarities

5. The nature of the blast phenomena measurement imposes certain constraints and requirements on equipment and personnel that are not required in other WES instrumentation activities (Figure 2). Extremely high levels of shock, vibration, pressure, and temperature necessitate that measurement-system components be dispersed to minimize damage to equipment and danger to personnel. Transducers must be located at the point where shock and vibration conditions are usually extreme. The center of an explosion is designated as ground zero.

6. Signal-conditioning equipment and recorders are typically placed in locations sufficiently remote from ground zero, so that they will survive the test and function satisfactorily during the measurement time. The long cables between the transducers and signal-conditioning equipment create additional calibration problems which are the main point of interest in this report.

7. In blast phenomena measurement everything happens in a "split second." Thus, the measurement system response time must be as short as possible.

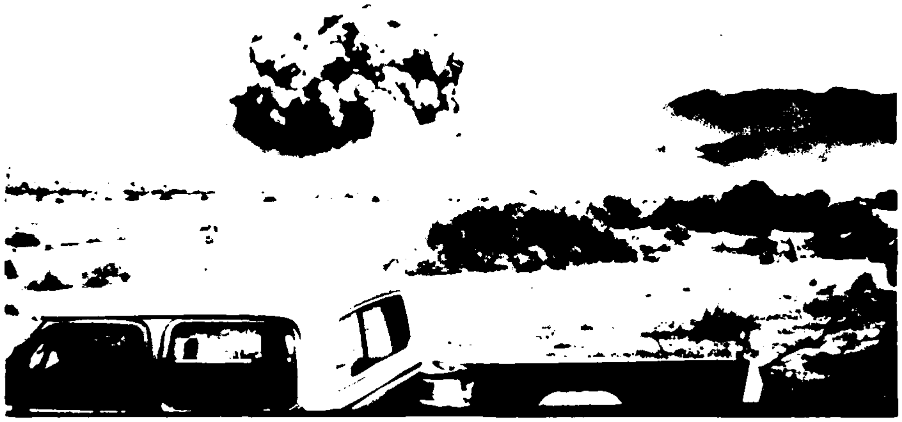


Figure 2. Example of blast phenomena to be measured

Research Motivation

8. Blast phenomena research goals frequently require data that exceed the state of the art in measurement technology. Therefore, in intermittent instances measurement data conflict with what seems reasonable for a physical process. In such cases it is necessary to reassess the measurement system involved and attempt to set well-defined bounds on what can and cannot be achieved at a given cost.

9. During 1983 one of the test series at Fort Polk, La., produced data that were considered unsatisfactory for the target research goals. Discussions of these data resulted in an agreement to examine the entire measurement procedure in detail. This analysis was initiated to examine the calibration procedures then in use at Fort Polk and other field sites where WES blast phenomena tests are conducted. It also addressed possible changes in instrumentation calibration techniques whereby measurement accuracy can be improved.

Scope of Research

10. Strain-gage bridge-type transducer calibration at WES and the measurement system electrical calibration in the field by the standard

operating procedures (SOP) are examined in this study. Comments relating to recording and data reduction are, however, valid for all types of transducers. The electrical circuit calculations performed were limited to a static analysis (i.e., only resistive elements were considered). This study does not address the transient electric or mechanical response nor the long-term drift of the transducer and measurement system.

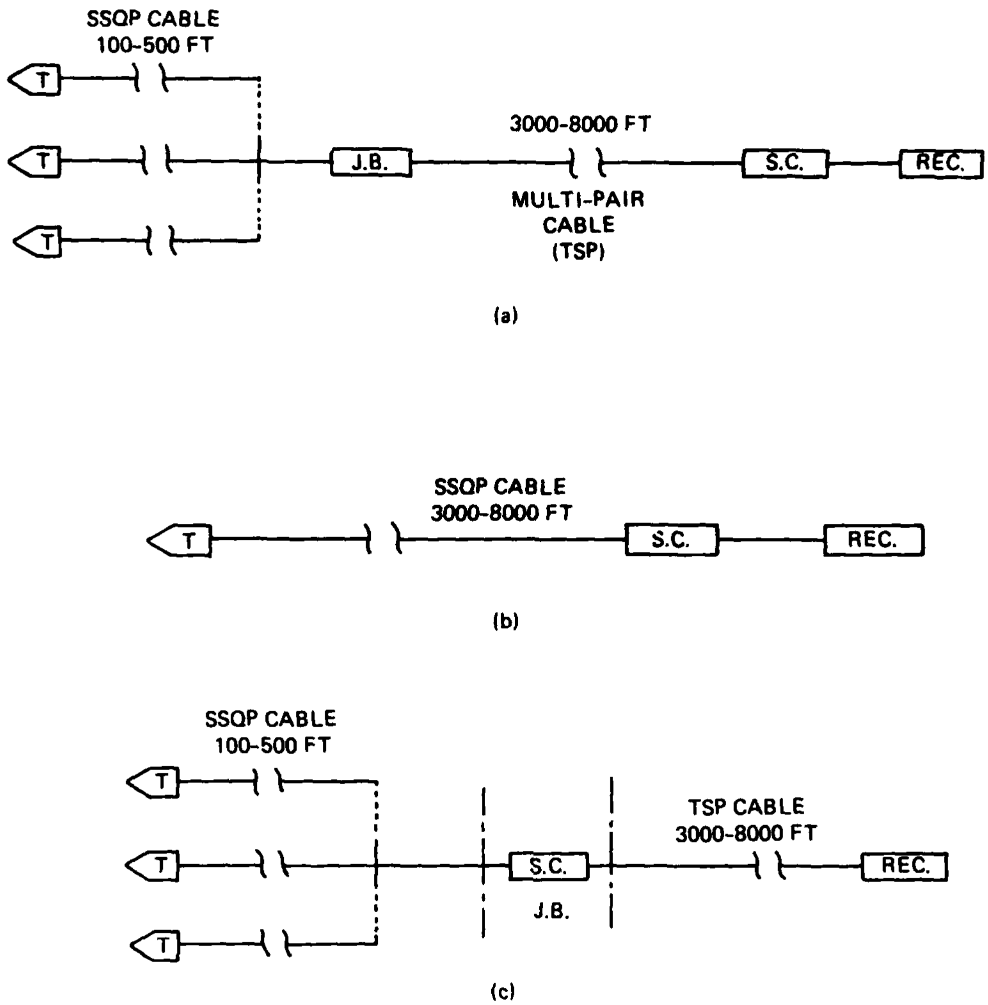
PART II: WES CURRENT MEASUREMENT TECHNIQUES

Field Measurement Installation

Blast phenomena system configurations

11. Assurance of equipment and operator safety necessitates the use of long cables to connect different parts of the measurement system, pictured in Figure 3. The block diagram in Figure 4 shows three measurement system configurations, each having definite advantages, disadvantages, and percentage of use in the total measurement effort by ISD. By comparison, in the system

Figure 3. Example of long cables used in blast phenomena measurement



SSQP = SHIELDED, STRANDED QUAD PAIR
TSP = TWISTED, SHIELDED PAIR
J.B. = JUNCTION BOX
S.C. = SIGNAL-CONDITIONING BLOCK
REC = ANALOG RECORDING SYSTEM

Figure 4. Different measurement system configurations

configurations illustrated in Figure 4, (a) consumes less time to install if multiple measurements are required and (b) is quicker to install if only a few measurements are required. Although in (c) the error due to the use of long cables is eliminated physically, this type is seldom used because of the complexity of the installation and measuring procedure. In approximately 90 percent of the total current blast phenomena testing, (a) is used.

Signal-conditioning unit

12. Figure 5 shows the circuit diagram of a standard WES signal-conditioning unit (DAM 103A Model). This unit contains the following:

- a. Two amplifiers.
- b. Balance potentiometer circuit.
- c. Excitation source and switches.
- d. Calibration relay with switch.
- e. Feedback resistor.

Cables used in the transducer measurement circuit

13. One or both of two different types of cables are used in a typical field measurement circuit. In general, the amplifiers and the excitation sources are connected to transducers by shielded, stranded quad pair (SSQP) cables. In some cases the amplifiers and the excitation sources are connected to junction boxes by 20 or 50 twisted, shielded pair (TSP)* cables. The transducers are connected to the junction boxes by (SSQP) cables. The cable between transducer and signal-conditioning unit is the section that most affects system calibration.

Field Operating Procedures

Procedural steps

14. The steps involved in a typical measurement procedure are listed below:

- a. The location of junction boxes is marked at prescribed distance from ground zero.
- b. The required number of cables are reeled out from the junction box area to the instrumentation trailers.
- c. The ends of each cable are tagged with its appropriate identification number (i.e., 1, 2, 3, ---, n).
- d. Junction boxes containing terminal strips are installed. Four terminals constitute a set. Each set is numbered in sequence (i.e., 1, 2, 3, ---, n).
- e. The cables and the terminal sets having the same number are connected at the junction box and the corresponding terminal sets in the instrumentation trailer.

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* Otherwise the SSQP-type cable is used.

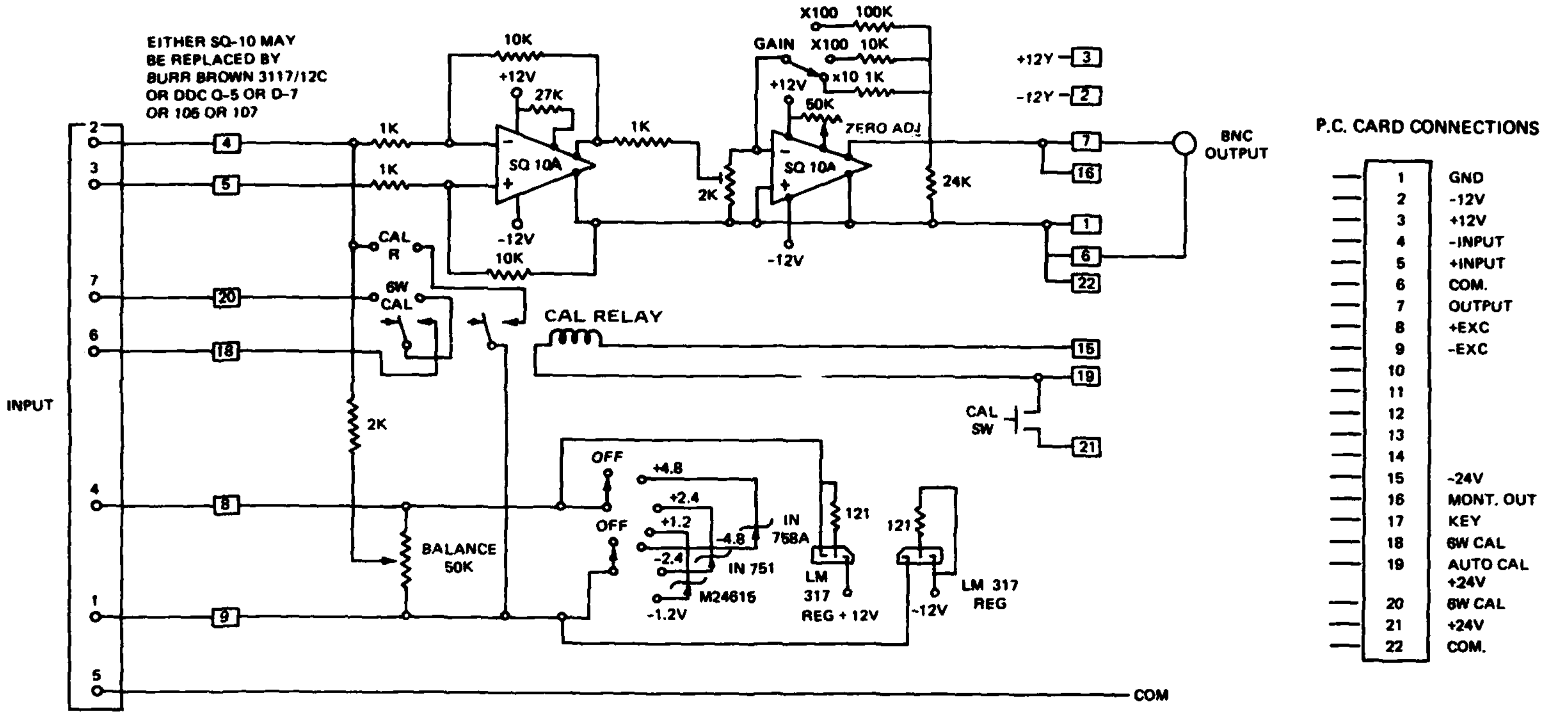

Figure 5. DAM 103A amplifying and signal-conditioning unit

f. The connection from the trailer terminal strips to the input of the signal-conditioning units and from the signal-conditioning units to the tape recorders is performed inside the trailer.

g. The primary cable troughs are cut in the ground along the perimeter of the overall test area. Then, as needed, the smaller distribution troughs leading to each specific test area or structure as gage connections are cut, and check out is started.

h. Each cable is numbered as it is reeled into the primary cable trough.

i. The individual conductor at one end of the cable mentioned in step h is connected to its matching set in the terminal junction box.

j. The other end of the cable mentioned in step h is connected to its assigned gages.

k. Each gage is checked with its cable, signal-conditioning unit, and its assigned channel on the tape recorder machine.

l. Shunt calibration resistor values are calculated.

m. The calibration resistors are installed in the signal-conditioning units.

n. The signal-conditioning units are balanced and the tape deviations are set by switching the calibration resistors into and out of the measurement circuit.

o. The calibration resistors are switched in.

p. The amplifier gain (and frequency modulation (FM) tape deviation) is set, using the voltage resulting from step o, so that the predicted peak value will give a tape deviation of 100 percent.

q. The calibration resistors are switched out.

r. The recording system is ready to record test data at this point.

s. Prior to a test the calibration steps (cal-steps) are recorded on tape. The cal-step record is made with the same gain and zero as will be used during the test. The cal-step record is registered as close in time to the test as practical. For most tests the operating sequence is automatically controlled and the cal-steps are recorded within a few seconds prior to a test.

t. During an automatically controlled test sequence the tape continues to run from a time prior to the cal-step phase through the blast test event and for a predetermined time after the event.

u. After a test the tape reels are rewound.

v. A light beam oscillograph is used to get a "quick-look" paper record of the measured data for field personnel to examine. This is done by playing back the recorded data on a reproduce tape machine.

A typical format for data recorded on a reel of magnetic tape is shown in Figure 6.

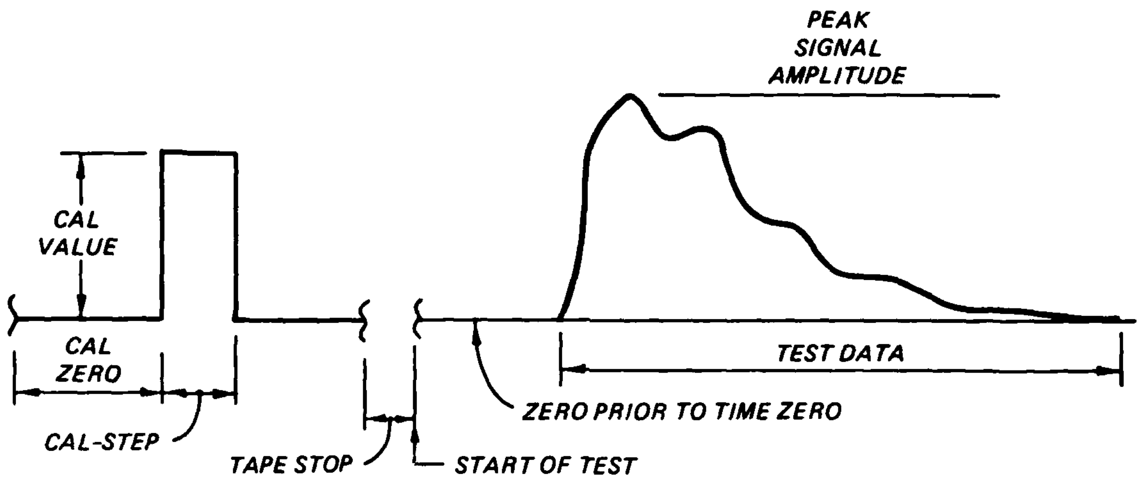

Figure 6. Analog representation of the shunt calibration resistor "cal-step" and the measured data

Recording system

15. Tape recorders with 32-track heads are usually used on WES blast phenomena tests because of the large number of signal channels involved. Generally, track 32 of each machine is dedicated to the recording of the Inter-Range Instrumentation Group (IRIG) time code signal, which is supplied by a common-time code generator, while track 31 of each machine is reserved for the zero time signal. This leaves 30 tracks per machine for the recording of analog data. Seven tape speeds are available and are related in ascending order by a factor of 2; e.g., 1-7/8, 3-3/4, 7-1/2, 15, 30, 60, and 120 inches per second (ips).* Frequency response of the recorder varies directly with tape speed, reaching a maximum of 40 kHz at 120 ips (for intermediate band tape machines) and reducing to 20 kHz at 60 ips, 10 kHz at 30 ips, etc. For a

* A table of factors for converting non-SI units of measurement to SI (metric) units is given on page 4.

high frequency (wide band) tape machine the recording capability is essentially twice that of an intermediate band machine, i.e., 80 kHz at 120 ips, 40 kHz at 60 ips, etc.

16. Compromises in the selection of a wide band tape recorder rather than an intermediate band tape recorder include a lessening of adjacent track isolation and somewhat lower signal-to-noise ratio. When a FM recording technique is used, signals can be recorded down to zero frequency (dc). On the other hand, using the direct record technique* will shift the recorded frequency band so that higher frequencies can be recorded but not frequencies below approximately 300 Hz. At the time of this analysis high frequency machines were available to record up to 600 kHz (FM) and 2 MHz (direct). With rare exception, recording response to zero frequency direct current (dc) is required in blast phenomena tests. This necessitates the use of FM record/reproduce electronics in the tape recorder. An exception to this occurs when techniques such as time division multiplexing and pulse code modulation (PCM) are used. The high frequency bit rate of the multiplexing system necessitates the use of direct record/reproduce electronics in the tape recorder. Multiplexing permits many channels of data to be recorded on one magnetic tape track and is the most efficient way to pack data on tape. Total cable length requirements are reduced if the multiplexer units are located closer to the transducers than to the recorders. The compromise, when multiplexing data, is a decrease in the highest frequency recorded per channel as the number of channels per track increases. Multiple data channels per tape track can also be achieved by using multiplexed PCM (another digital technique).

17. Calibration steps are recorded during all blast phenomena tests regardless of the recorder type or recording format. The so-called "cal-steps" are a simple and effective end-to-end electrical check of the entire recording system. These steps are recorded immediately prior to the blast, so that there is minimum chance of time variations in the electrical characteristics of the recording system. Each cal-step has a value directly related to a physical quantity to be measured. During the data reduction process, the cal-step on each channel is digitized along with test data. Magnitude of the physical parameter being measured is determined by ratioing each digitized

---

* In this technique the signal current in the head does not modulate the bias current but is merely added to it.

data point to the cal-step value. This procedure provides data values essentially independent of the gain of individual components of the system. Linearity of system components is verified during pretest check-out procedures. Linearity of signal-conditioning amplifiers and tape recorders is excellent (better than 0.1 percent), and errors due to minor deviations from perfect linearity are negligible. Multiple cal-steps on the record will contribute essentially nothing to the data quality because of the good linearity of the recording system. Nonlinearity of the transducers can be better handled by use of a nonlinear equation fitted to the data points rather than with multiple cal-steps.

18. Effective data resolution during data reduction is limited by the signal-to-noise ratio of the magnetic tape recorders and by the accuracy of the predictions. Instrumentation Services Division (ISD) technicians usually set recording system gain so that the predicted peak measurement value will result in 100 percent of the full-scale deviation of the FM recording amplifier in the tape recorder. In some cases the prediction is meant to be near the values to be measured, and, in this case, the recording system is set to give a result in 50 percent of the full scale. If the actual physical input peak exceeds the predicted peak value, the recorded signal will be limited in the amplifiers, resulting in an error in the peak value. In the opposite extreme case, where the actual data peak is much less than the predicted value, system noise limits the effective data reduction resolution. Multiple cal-steps are <u>not</u> an effective noise abatement technique. A block diagram of a typical field data collection system is given in Figure 7. In every recording/reproducing procedure noise does exist; therefore, it is very important to define limits on which the measurement procedure will be considered acceptable or not, as far as noise is considered. Bounds are set on the signal-to-noise (S/N) ratio in a way that if its value exceeds a certain amount, then the recorded data are not considered acceptable.

19. From the design of the tape recording machine used in ISD measurement procedures, the S/N value is a function of tape speed and the IRIG band. Table 1 shows the S/N value (assuming that maximum deviation of the tape recording machine is 1.4 v in the recording/reproducing mode). This is not always the case in the ISD measurement procedures where the maximum deviation is sometimes set to be 1.0 v in the recording/reproducing mode. This is done because it is more convenient for the field site operator. In such a case

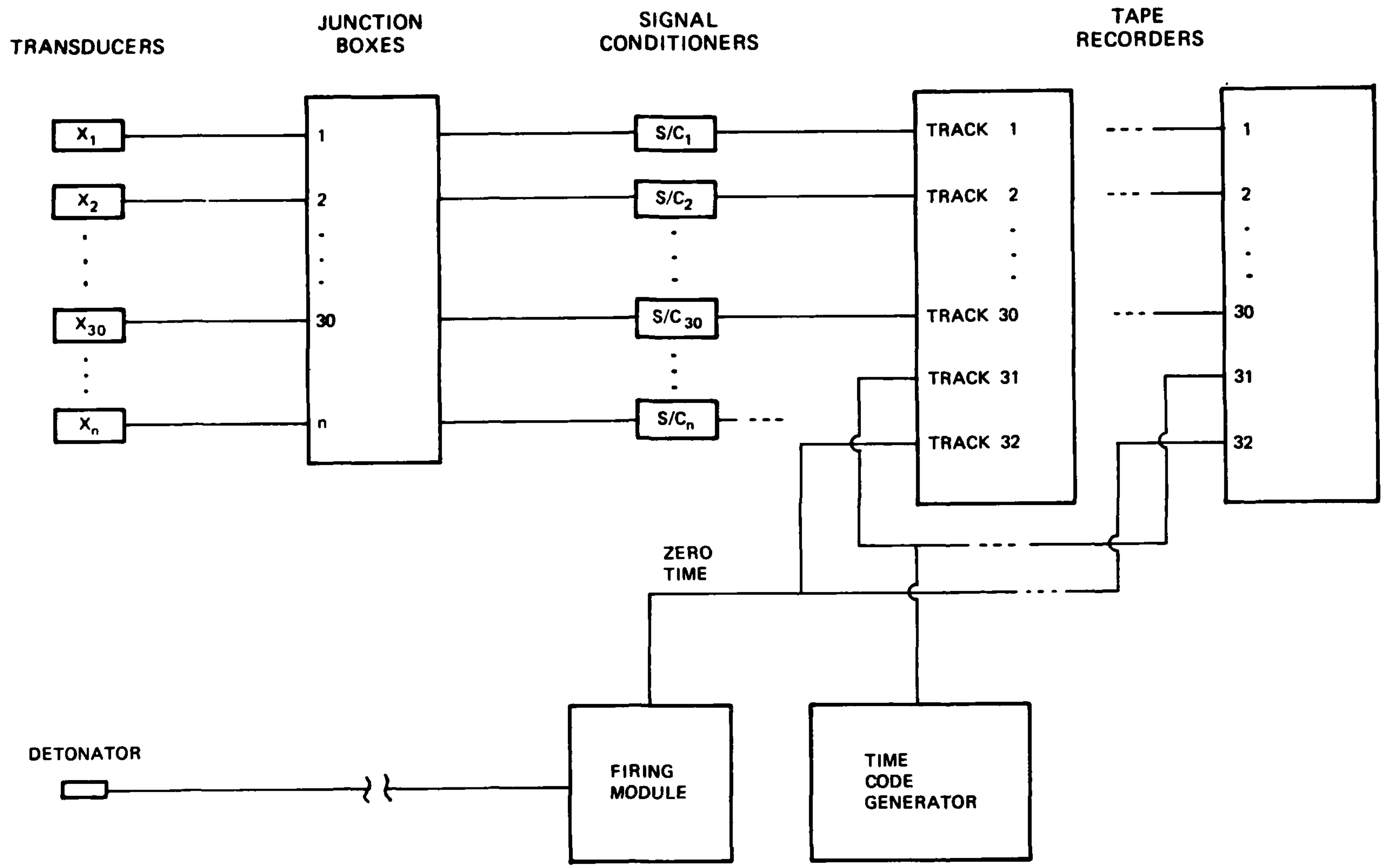

Figure 7. Recording system block diagram

with a given tape speed and IRIG band, S/N will be less than that mentioned in Table 1. If the noise magnitude measured peak to peak has a value up to 3 percent of the cal-step value,* then such noise is considered low, but if the magnitude of such noise is 10 percent of the cal-step value then it is considered unacceptable. Typical noise magnitude is assumed to be 5 percent of the cal-step value.

20. In the tape reproduce mode, within limits, increasing the tape speed will decrease the noise level, while decreasing the recording machine speed will increase the effective digitizing rate.

21. Figure 8a shows an oscillogram of a digitized pressure versus time record, while section S of the recorded data is expanded in Figure 8b, showing noise content in the recorded data.

Field Notes

22. All required notes from the field during the instrumentation system installation and checkout are recorded on one standard form. This field record is called the shot sheet.

23. A typical shot sheet has 13 columns and 32 rows, as shown in Figure 9. All the measurements are recorded simultaneously and each row on the shot sheet contains the required information associated with each measurement.

- a. Column 1 indicates the track number on the magnetic tape machine.
- b. Column 2 contains the measurement identification.
- c. Column 3 contains the serial number of the corresponding transducer.
- d. Column 4 contains the cable number connecting the transducer to the amplifier.
- e. Column 5 contains the corresponding amplifier number.
- f. Column 6 contains the full-scale predicted engineering unit.
- g. Column 7 identifies the polarity of the cal-step. When the measured signal has the same polarity as the cal-step, the following is standard:

---

* This value produces 50 percent of the voltage that the predicted peak measurement value will produce.

Kind of Measurement	Cal-Step Interpretation
Load	Compression
Strain	Tension
Displacement	The probe is moving into the barrel of the transducer
Acceleration	Movement of the accelerometer is from base to cap

h. Column 8 has the value of the corresponding $C^*_{a/o}$ (measured at the calibration room.

i. Column 9 contains the corresponding gage constant value.

j. Column 10 shows the cal-resistor value used in ohms (or kilohms).

k. Column 11 contains the value of the cal-step in engineering units equivalent to the value of the shunt resistor used in column 10.

l. Column 12 contains the value of the cal-step corrected for cable length.

m. Column 13 contains the percent of full-scale frequency deviation corresponding to the predicted peak measurement value.

Data Reduction

24. The ISD data reduction facility is designed to handle field and laboratory test data recorded on analog magnetic tapes. The most common recording format is 32 data tracks on 1-in.-wide tape. Fourteen tracks on 1-in.-wide tape is the next most common format handled. Field data tapes are played back in the ISD Data Reduction and Processing Facility at WES. Analog data are converted to digital values and stored on disk or magnetic computer tape. Digital data are scaled by using the calibration value recorded on the original tape as a reference. Digitizing rates are based on the expected frequency content of the recorded signals and determined by the researcher. The resulting data are reduced by the WES researcher when a selection of pertinent portions are requested.

25. A block diagram of the data reduction facility at the ISD at WES is shown in Figure 10. The sequence of steps in data reduction is shown in Figure 11. Figure 12 shows the data reduction facility at ISD.

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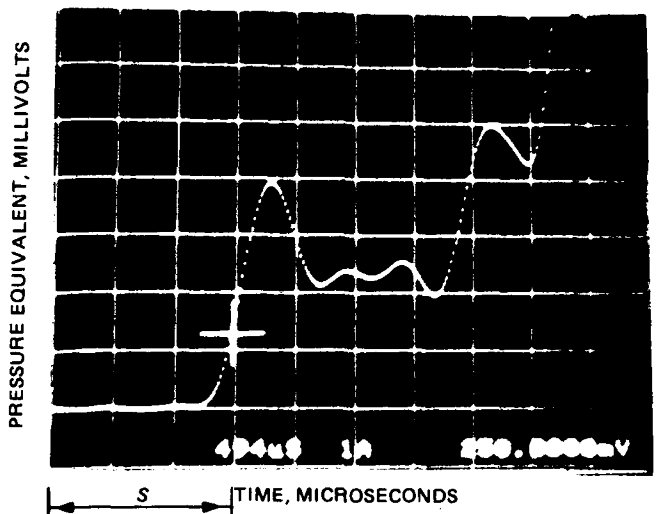
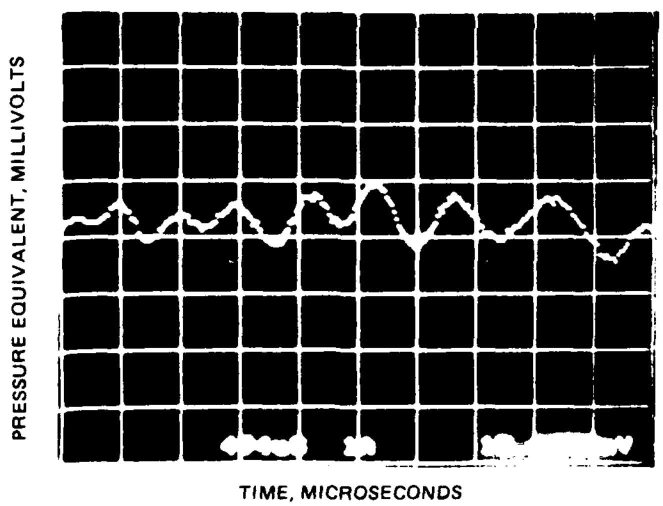
* This constant will be discussed in the following material.



a. Pressure-time record



b. Expanded section of record a. showing noise content in signal

Figure 8. Oscillograms of a digitized pressure-time record

PROJECT: ____________ PROJ. ENGR. ____________ PAGE ___ OF ___
DATE ________

TRK NO	GAGE MEAS.	SERIAL NO.	CABLE NO.	AMP NO.	ENG. PR. 100%	+/-	GAGE CA	RG K OHM	CAL R. K OHM	CAL EQUIV	CAL EQ CORR	CH NO
1												
2												
3												
4												
5												
6												
7												
8												
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32												

THIS LOG COVERS REEL NO.: ________ FROM ________ FT TO ________ FT

REEL NO.: ________

14 ___
32 ___
IPS ___

START ________
CAL IN ________
CAL OUT ________
SHOT ________
STOP ________

NOTES:

DENSITY:
HIGH ______
MED ______
LOW ______
VOICE:
EDGE A ______
EDGE B ______
TRACK ______
DIRECT ______
F.M. ______
NONE ______

Figure 9. The shot sheet

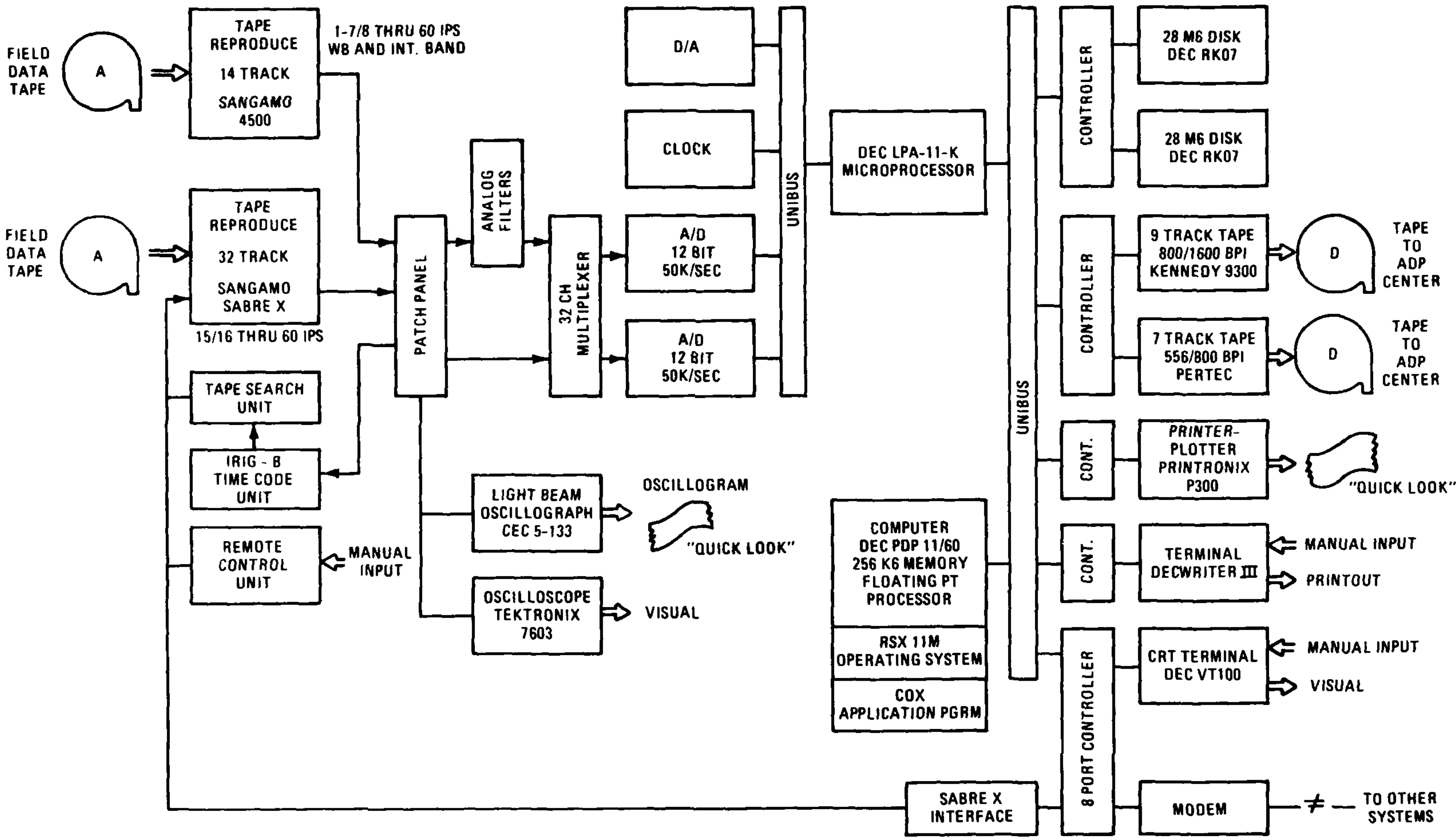


Figure 10. ISD data reduction facility block diagram

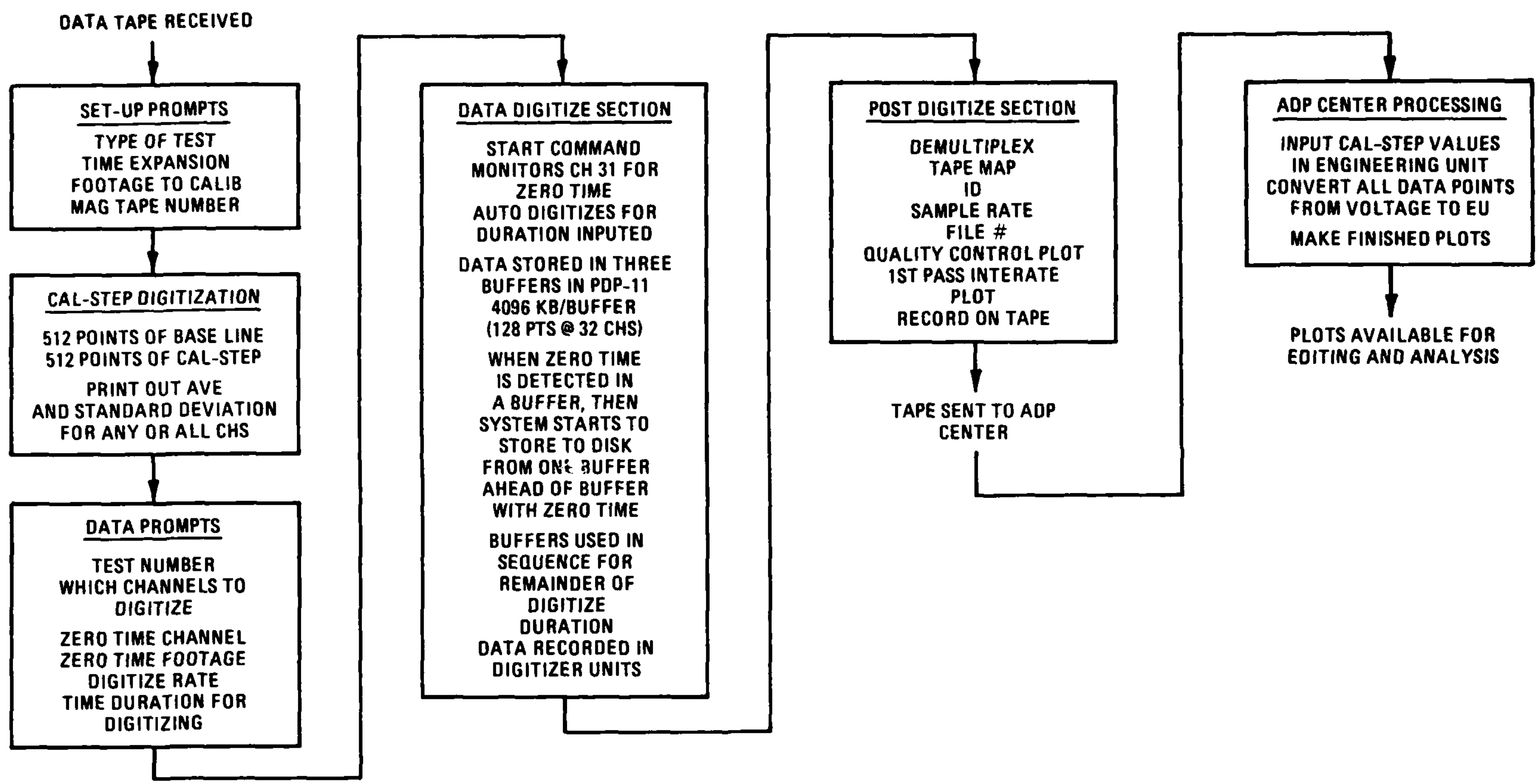


Figure 11. Sequence of steps in data reduction

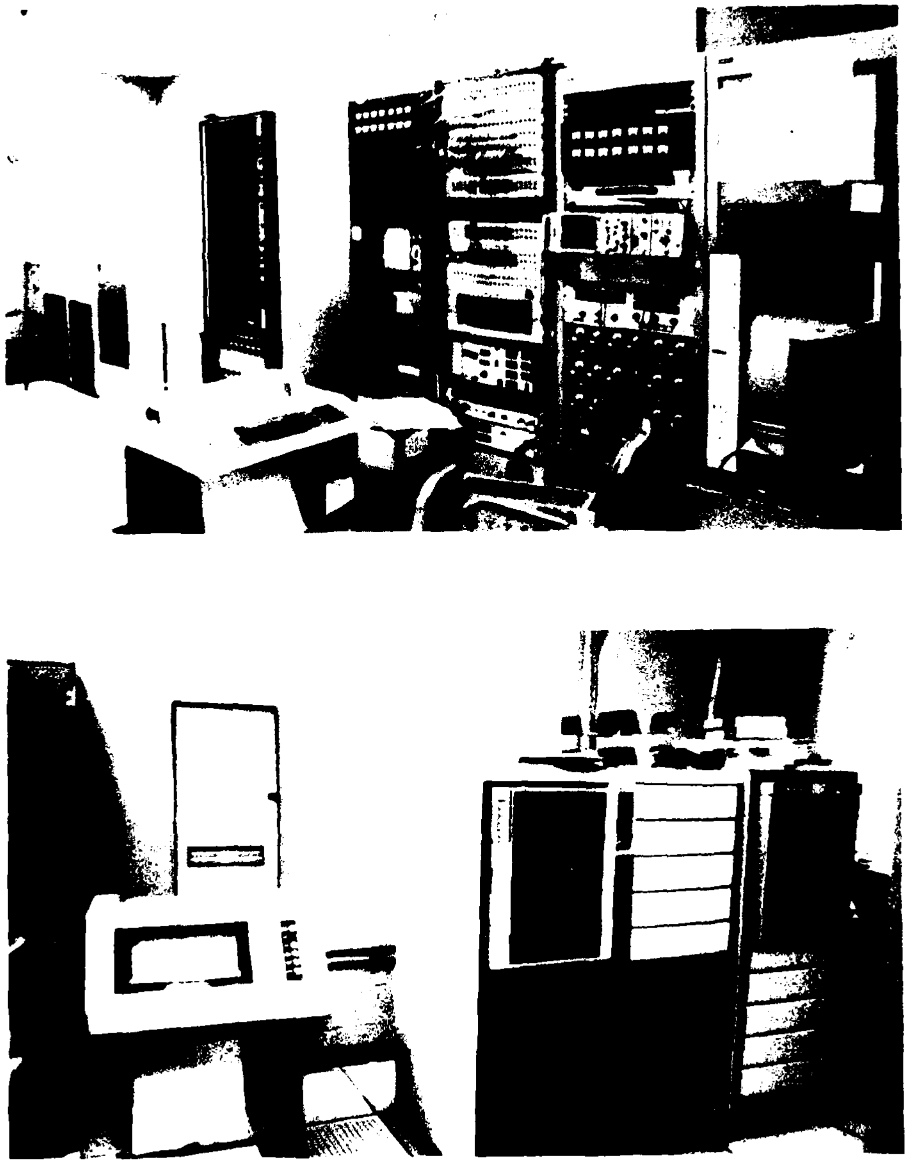


Figure 12. The data reduction facility at ISD

Calibration

26. The output voltage from a balanced measurement circuit is zero unless a physical input is applied to the circuit transducer or a shunt calibration resistor is switched into the circuit.

27. The characteristics of the measurement circuit are explained by the two curves described below:

a. One curve represents the relation between the applied physical input to the transducer and the corresponding output voltage.

b. A second curve represents the relation between the value of a shunt calibration resistor and the corresponding output voltage.

28. A complete interpretation of the measurement procedure is illustrated by Figures 13 and 14. In the laboratory a pressure cell was connected to a signal-conditioning unit by a short cable (effectively zero length), and a controlled pressure (known to a high precision) was applied to the pressure cell. Curve 1 represents the relation between the variable input pressure and the corresponding output voltage. All other parameters being held constant, the input pressure was removed completely and a variable shunt resistance

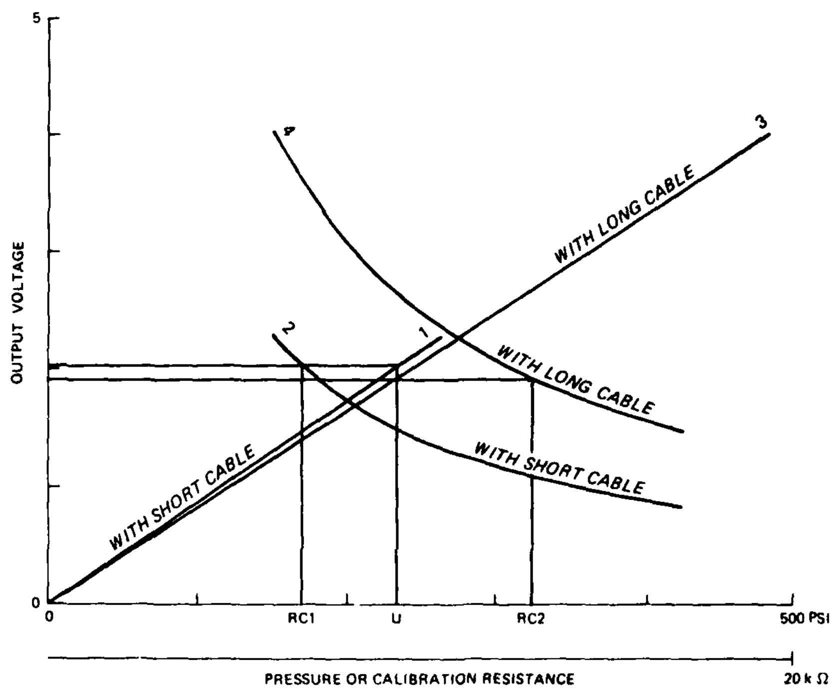


Figure 13. Calibration curves

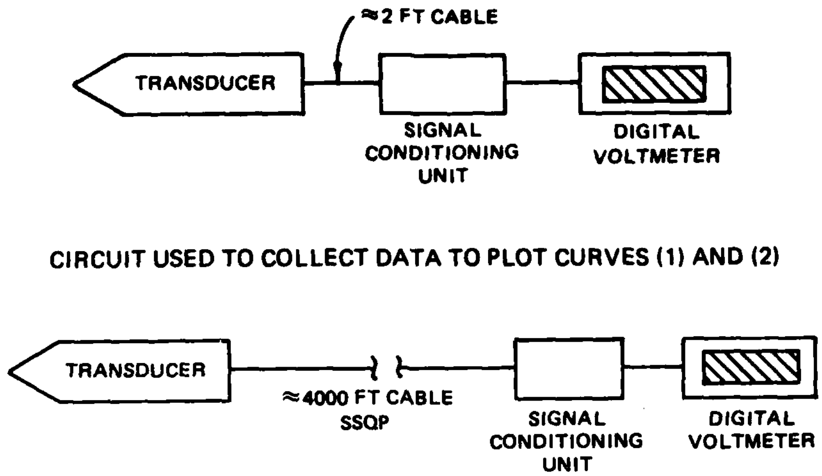


Figure 14. Circuits used to collect data to plot the curves in Figure 13

(calibration resistor) was connected across a defined arm of the pressure cell. Curve 2 represents the relation between the value of the variable shunt calibration resistor and the corresponding output voltage.

29. Curves 1 and 2 were valid only when a short cable was run between the pressure cell and the signal-conditioning unit. Next a known length of SSQP cable (about 4,000 ft) was introduced between the pressure cell and the signal-conditioning unit. This same procedure was repeated to obtain relations similar to those explained by curves 1 and 2, and the result was curves 3 and 4. The two circuits used to collect the data used in plotting curves 1 and 2 and curves 3 and 4 are shown in Figure 14. These tests show that the measurement circuit characteristics change every time a different length of cable is used between the transducer and signal-conditioning unit. It is clear that for any given physical input to a transducer there is an equivalent shunt cal-resistor value. For example, in Figure 13 curve 1 shows that the output voltage Vo is due to the application of some input pressure U to the measurement circuit with a very short cable connecting the pressure cell to the signal-conditioning unit. The same output voltage can be a result of shunting a defined arm of the pressure cell in the measurement circuit by a calibration resistor RCl (with the pressure removed). The location of RCl on the X-axis is determined by the use of curve 2. The same applied pressure U will produce another output voltage V_L from the measurement circuit with the 4,000-ft-cable running between the pressure cell

and the signal-conditioning unit. The location of V_L on the Y-axis is determined from curve 3. Curve 4 serves to determine the value of the calibration resistor RC2. This calibration resistor may then be used to develop the same amount of output voltage V_L from the measurement circuit with no pressure applied and the same 4,000-ft-length of cable running between the pressure cell and the signal-conditioning unit. Transducers calibrated in the laboratory at WES are normally connected to the signal-conditioning unit with a very short cable (zero cable length) and adequate data are collected under this condition. Such data could be used to plot curves similar to curves 1 and 2 in Figure 13. It would be impractical to make a laboratory check of each transducer with its corresponding length of cable in the field. The location of specific transducers correlated to test locations is not known at the time the transducers are calibrated at the laboratory. Thus, calibration cannot be performed with the installed length of cable simulated. The shunt resistor calibration technique is used to electrically calibrate the measurement circuit at a field site. Data from the zero cable calibration in the lab are used to compute the value of a shunt resistor used with a known length of installed cable between the transducer and signal-conditioning unit. Questions about this calibration procedure were asked by the Geomechanics Division personnel at WES. In the following sections of this report the answers to these questions are stated.

Pressure Cell Calibration

30. At WES, pressure cells under calibration are balanced and excited by a constant current source that is part of the signal-conditioning unit. Nitrogen gas pressure is applied to these pressure cells* from a manifold (Figure 15). This pressure is controlled by a regulator valve and measured in pounds per square inch with a very accurate reference gage.

31. The electrical output from the pressure cell under calibration is amplified in the signal-conditioning unit and the output from the unit is measured in volts by a digital multimeter (type and accuracy of these instruments are given in Appendix A).

---

* Nitrogen gas pressure is used when low and medium pressure cells are calibrated. Hydraulic pressure is used to calibrate high pressure cells.

a. Gas pressure manifold

b. Hydraulic pressure

Figure 15. Manifold from which pressure is applied to the cell under calibration, and one kind of calibration chamber

32. The applied pressure is adjusted in preselected steps and five readings are taken, the last one corresponding to the maximum pressure within the range of the pressure cell under calibration (or the highest pressure produced by the calibrating system). At each reading, the applied pressure and the output voltage are recorded on a standard calibration data sheet. This portion of the calibration procedure determines the electrical output signal from the pressure cell in response to the input pressure under defined circuit conditions.

33. After completing the above steps, the pressure is removed completely. A defined arm of the pressure cell is then shunted in steps with four different values of resistance. At each step, the value of the shunt reference resistance and the output voltage is recorded on the same data sheet. This portion of the calibration procedure determines the shunt cal-resistor equivalence to applied pressure. Figure 16 shows block diagrams of static mechanical and electrical calibration circuits.

34. Three factors are then computed by using the recorded data in the data sheet, as shown in Figure 17. These factors and the procedures used in their computation are mentioned below:

a. S factor. The applied pressure is divided by the output voltage at each point in the pressure cell response data, the average of these divisions being the S factor.

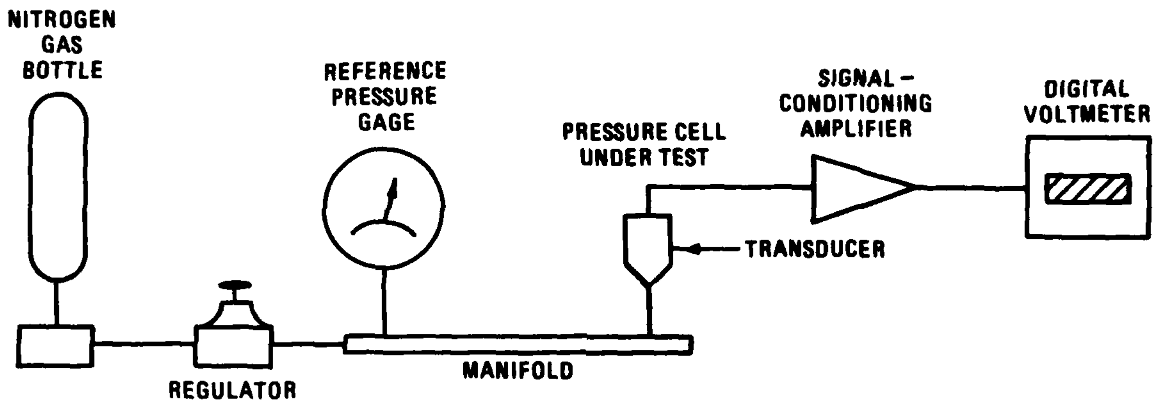
b. K factor. The resistive value of Rg (discussed in detail in paragraphs 78 and 85) is added to the value of the shunt calibration resistance and multiplied by the corresponding output voltage at each point in the electrical calibration response. The average of all points is the K factor.

c. $C_{a/o}$ factor. This factor is the result of the multiplication of the S factor by the K factor.

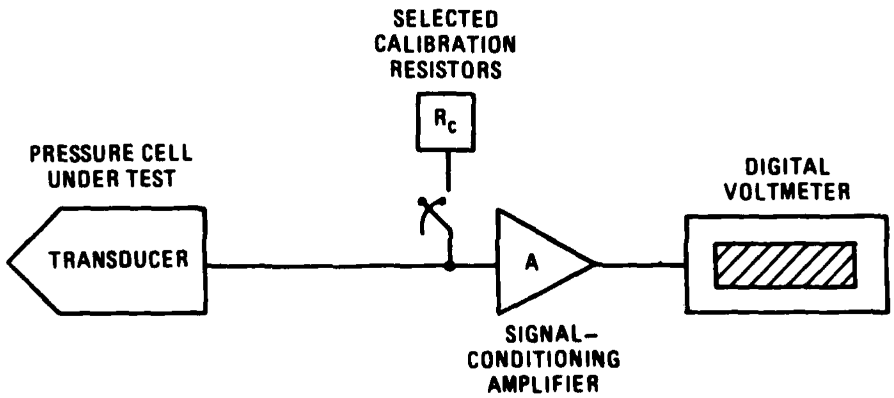
Accelerometer Calibration

35. All WES accelerometers can be calibrated statically, dynamically, or both.

a. Static calibration. The reference acceleration input to the accelerometer is created by the use of a centrifuge. The procedure for collecting data on the accelerometer response, the electrical calibration response, and the computation of S, K, and $C_{a/o}$ factors is the same as mentioned in paragraphs 30 through 34.



a. Block diagram of static pressure calibration circuit



b. Block diagram of static electric calibration circuit

Figure 16. The electro-mechanical calibration of pressure cells

STATIC ACCELEROMETER CALIBRATION

TRANSDUCER S/N ________ MODEL ________ RANGE ________ G DATE ________ C_A ________ KΩG

SYSTEM ________ GAIN ________ EXCITATION ________ V BY ________ NONLINEARITY ___% REPEATABILITY ___%

CABLE LENGTH ________ GAUGE ________ TYPE ________

S_A ________ G/VOLT

TRANSDUCER RESPONSE			
N	G	E_G	S

ELECTRICAL CALIBRATION RESPONSE				
R_c	R_g	E_c	K	K_c

COLOR CODE

1 ________

2 ________

3 ________

4 ________

5 ________

6 ________

7 ________

FULL BRIDGE ☐
HALF BRIDGE ☐
COMPLETION
RESISTORS ________ Ω

N – SPINTABLE ROTATION IN REVOLUTIONS PER MINUTE
G – EQUIVALENT ACCELERATION FIELD IN GRAVITIES
E_G – OUTPUT OF TRANSDUCER DUE TO ACCELERATION IN VOLTS
S – SLOPE IN GRAVITIES PER VOLT
R_c – SHUNT CALIBRATION RESISTOR IN KILOHMS
R_g – EQUIVALENT GAGE RESISTANCE IN KILOHMS
E_c – OUTPUT IN VOLTS PRODUCED BY SHUNTING WITH R_c
K – SHUNT VOLTAGE CONSTANT IN KILOHMS VOLTS
C_A – SHUNT CALIBRATION CONSTANT IN KILOHMS GRAVITIES

$S = \frac{G}{E_G}$

S_A = AVERAGE OF S

K_c = AVERAGE OF K

$K = E_c(R_c + R_g)$

$C_A = (K_c)(S_A)$

$\text{NONLINEARITY} = \frac{S - S_A}{S_A}$

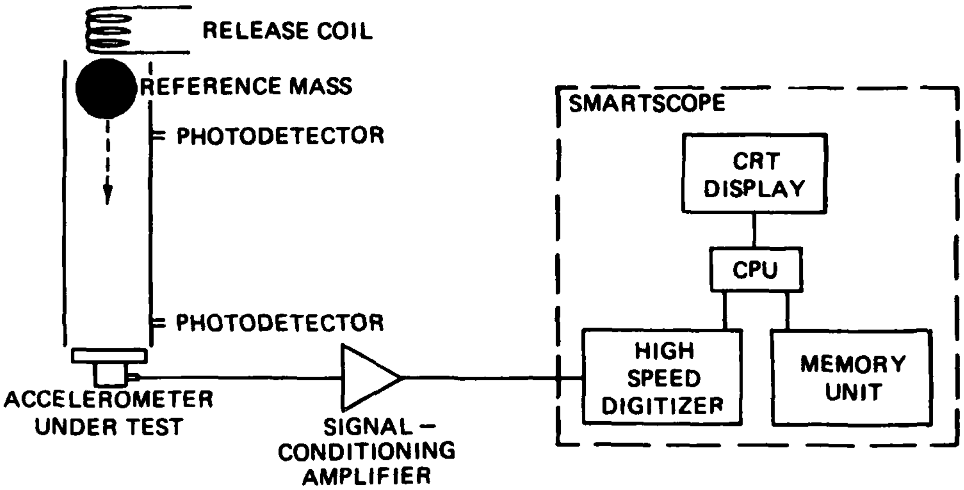
$\text{REPEATABILITY} = \frac{K - K_c}{K_c}$

WES FORM NO. 1972
AUGUST 1971

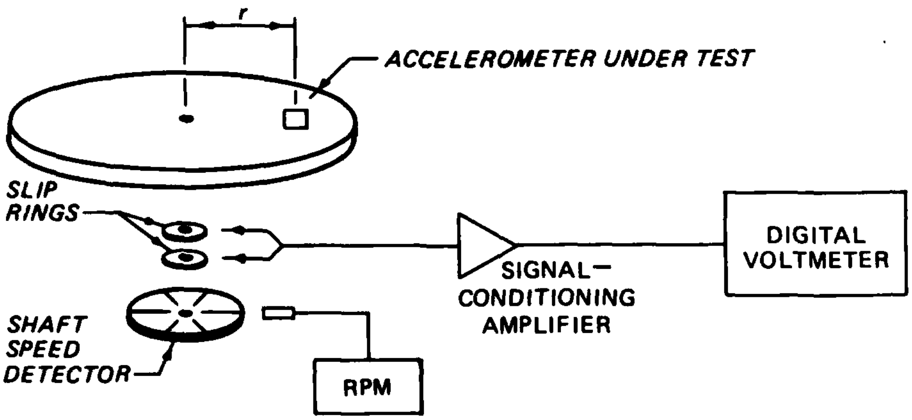
Figure 17. A typical calibration data sheet

b. <u>Dynamic calibration</u>. A calibrator developed by ENDEVCO Corp. is used for dynamic calibration of accelerometers. In this machine a solid metallic ball is dropped vertically through a cylindrical tunnel so as to hit a plate supporting the accelerometer under calibration. Output signal from the accelerometer during impact of the calibration ball is represented by a curve displayed on the "Smartscope," a digital recording oscilloscope. This curve is compared with a curve from a standard accelerometer mounted on the same fixture, and a slope average sensitivity of the accelerometer is computed.

Figures 18 and 19 show the accelerometer calibration (static and dynamic) block diagrams and a photo of the dynamic calibration instruments, respectively.



BLOCK DIAGRAM OF
DYNAMIC CALIBRATION CIRCUIT
FOR ACCELEROMETERS
USING A REFERENCE MASS



BLOCK DIAGRAM OF
STATIC CALIBRATION CIRCUIT FOR ACCELEROMETERS
USING A CENTRIFUGE

Figure 18. Block diagram of dynamic and static circuits for accelerometer calibration

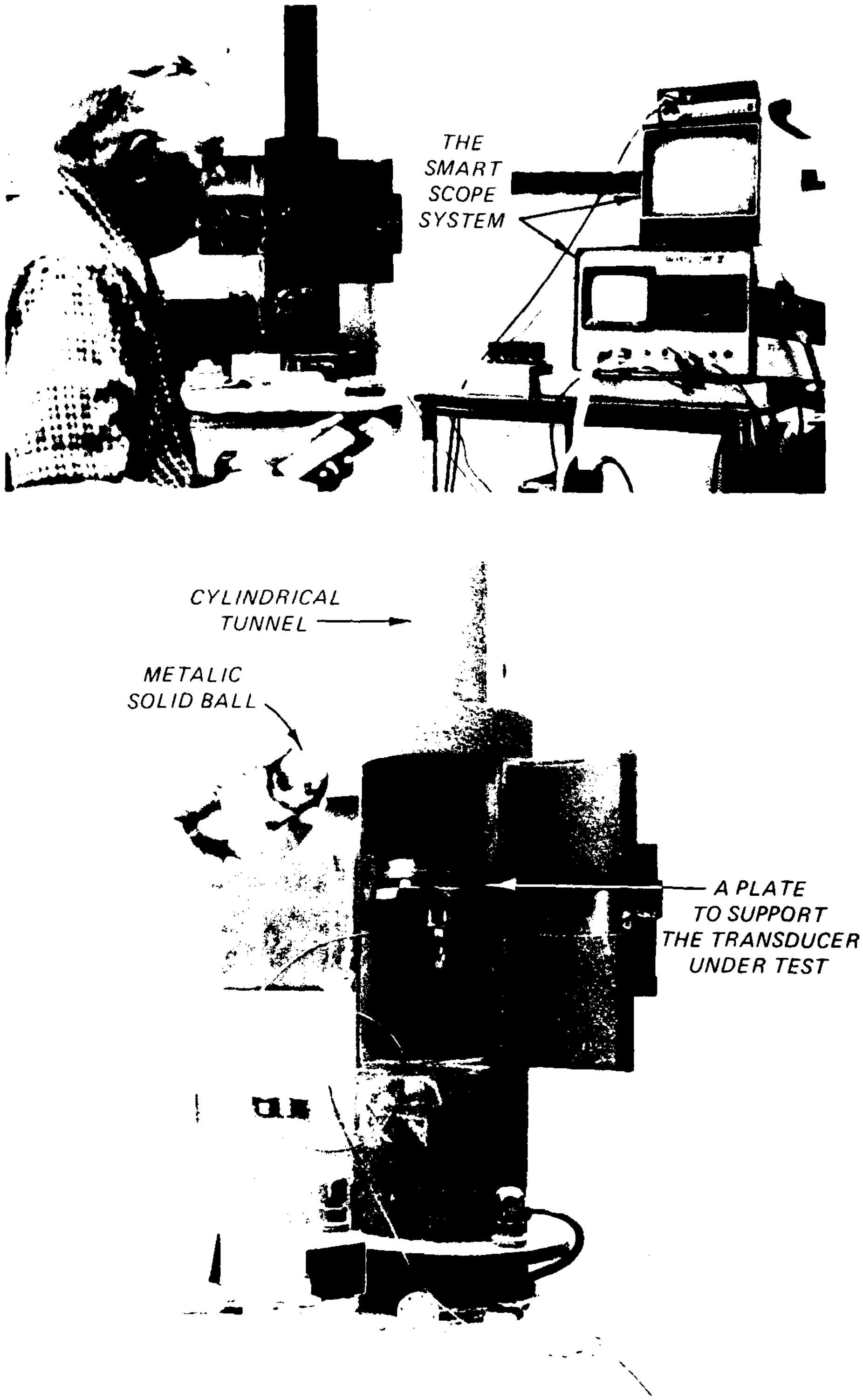


Figure 19. The dynamic calibration system of the accelerometers

PART III: STATISTICAL ANALYSIS OF MANUFACTURING TOLERANCES IN TRANSDUCERS USED IN BLAST PHENOMENA TESTS

Analysis Techniques

36. The consistency of the quality of the production of the transducers was analyzed statistically. In order to illustrate the techniques used in this analysis the calibration data supplied by the manufacturer were compared with the data developed by WES calibration.

37. Two samples of accelerometers made by ENDEVCO and their corresponding calibration data were available at the time of this analysis. One sample consisted of 111 25-g accelerometers and the other consisted of 50 200-g accelerometers.

38. Histograms and normal curves were plotted against percentage relative frequency with the aid of an HP-85 computer. The histograms were used for the reasons listed below:

- a. To determine the deviation (percent error) in sensitivity factor (S) derived from laboratory calibration in WES.
- b. To determine the distribution of the ratio between open circuit sensitivity (ENDEVCO calibration) and $C_{a/o}$ (defined in paragraphs 26 through 29-Calibration). This ratio was used as an index in the quality control evaluation.
- c. To examine the distribution of the "active arm" resistance values in the accelerometer population.
- d. To determine the distribution of open circuit sensitivity (S1) values supplied by ENDEVCO.

Deviation (Percent Error) in Sensitivity Factor (S) Computed from Calibration Procedure

39. Forty points from available data on the accelerometer response were selected at random. At each point the difference between the average sensitivity and the sensitivity at that point was computed, and the result was the forty values of deviation. Figure 20 shows a histogram used to find the distribution in these deviations. Deviation in the sensitivity value could range from 0 to 0.96 percent. This means that for the case under study, maximum error introduced to the value of S when calculating its arithmetic mean average (AMA) is 0.96 percent. This potential error is within experimental

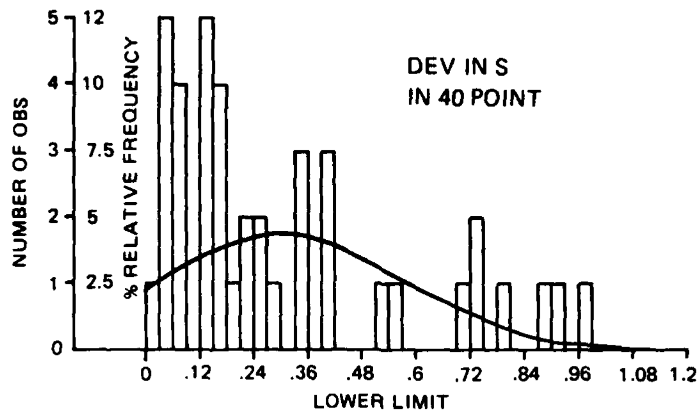


Figure 20. Histogram to find deviation in S

tolerance and the results obtained through using the AMA value S are acceptable for field use. Keeping in mind the mean value of S is 0.3 percent which appears in 36 percent of the total points in this sample.

Distribution of S1/$C_{a/o}$ Ratio (η)

40. The open circuit sensitivity (S1) (manufacturer's calibration) of the sample 25-g accelerometers was plotted against the $C_{a/o}$ factor (WES's calibration) in Figure 21. A study of this plot suggests that our sample of this type of accelerometer consisted of two different production lots. Those with J in the serial number had consistently higher bridge impedance. Those with E in the serial number had consistently lower bridge impedance. Two histograms were plotted, one for each production lot (Figure 22); the histograms were for the ratio η , where $\eta = S_1/C_{a/o}$. (η units are in mv/g/kΩg)

From histogram E:

$0.38 \le \eta \le 0.44$ (in 100 percent of the accelerometers)

From histogram J:

$0.3 \le \eta \le 0.4$ (in 96.78 percent of the accelerometers)

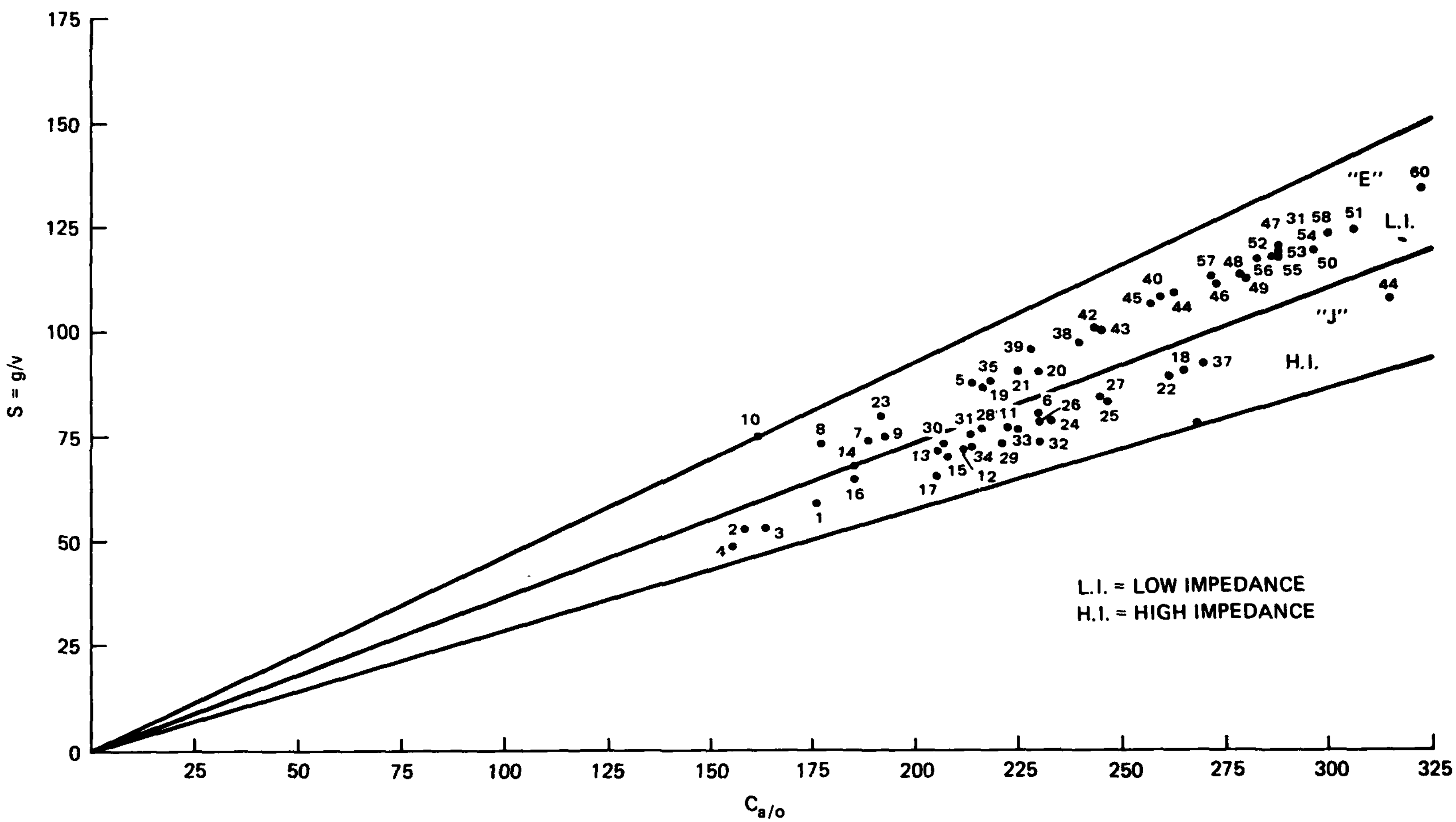


Figure 21. Accelerometer sensitivity versus calibration constant

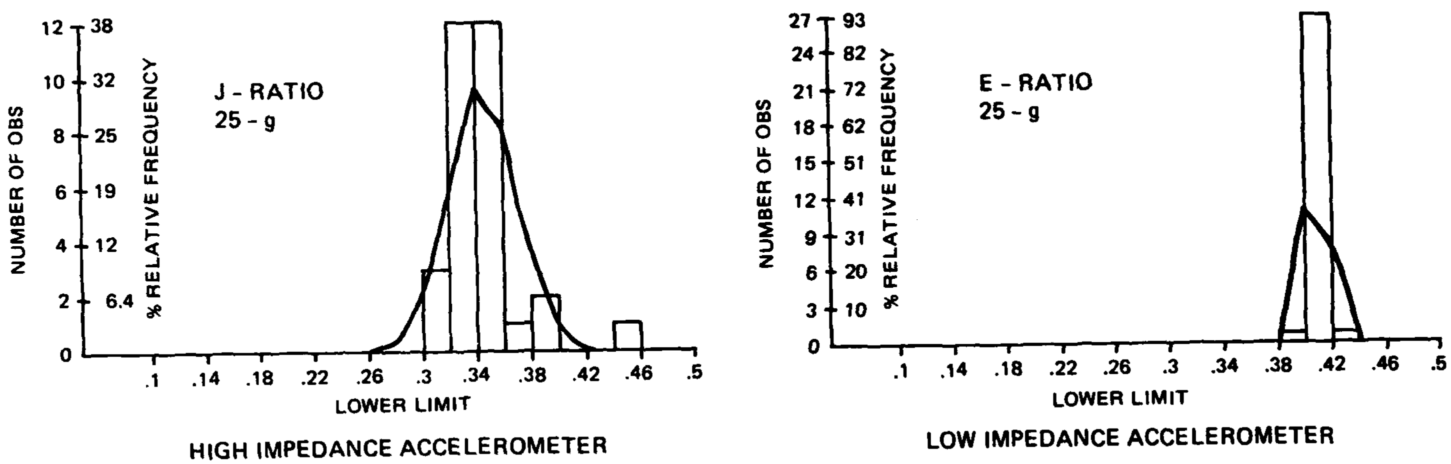


Figure 22. Histograms to find η range in 25-g accelerometer

No plot equivalent to Figure 21 was made for the 200-g accelerometer sample but histograms for its two lots (the 200-g accelerometer sample contained two lots also, those with K in the serial number and those with J in the serial number) were made (Figure 23).

From histogram K:

$$0.33 \leq \eta \leq 0.35 \text{ (in 100 percent of the accelerometers)}$$

From histogram J:

$$0.33 \leq \eta \leq 0.35 \text{ (in 100 percent of the accelerometers)}$$

Since the fluctuation in the value of η in each production lot is consistent within permissible range, the results of both calibrations (i.e., manufacturer's and WES's) are consistent. This result supports both the WES calibration procedure and the manufacturer's quality control.

41. The manufacturer's calibration is the relation between the input acceleration and the corresponding output voltage represented as a ratio with a unit of mv/g. The WES calibration is given in terms of the ratio between the input acceleration and the shunt calibration resistor value. This will be used to shunt a defined arm in the accelerometer's circuit bridge to represent that acceleration in engineering units. This ratio is represented in kΩg units.

Distribution of Accelerometer Bridge Active Arm Resistance Values

42. In order to find a range for the value of resistance for each active arm R_a the data on the 111 accelerometers of 25-g range were stored in the computer used for this analysis. These data were used to compute and to plot histograms for:

a. Accelerometer input resistance.

b. Accelerometer output resistance.

c. Input resistance/output resistance ratio of the accelerometer.

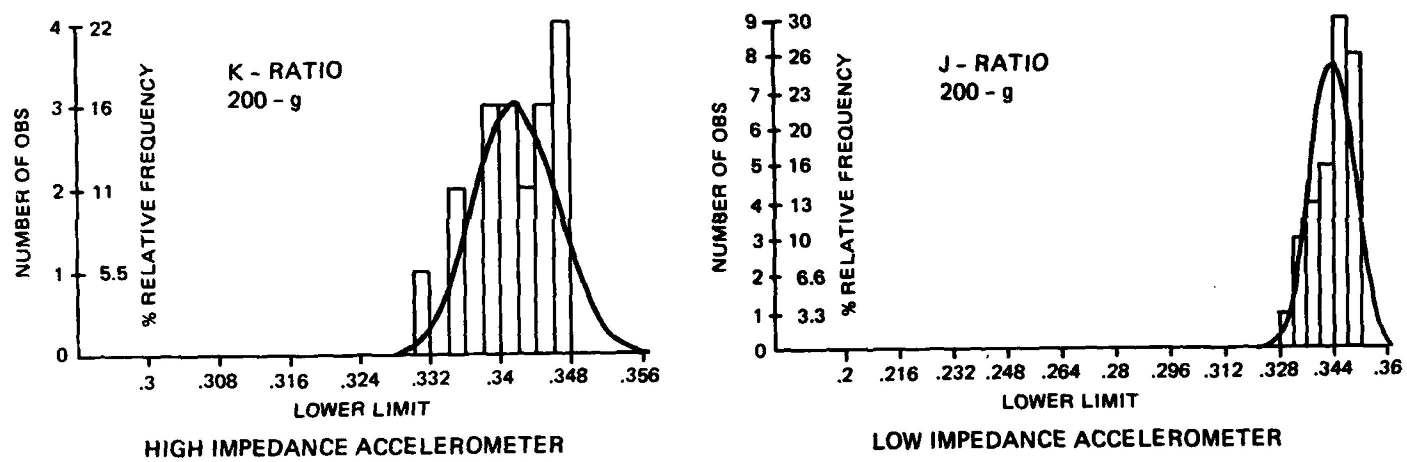


Figure 23. Histograms to find η range in 200-g accelerometer

Information from the three histograms (Figure 24) was used to calculate the bounds on the active arm resistive value as:

$0.64\ k\Omega \leq R_a \leq 1.28\ k\Omega$, where R_a is the active resistive value. (Calculations are given in Appendix B).

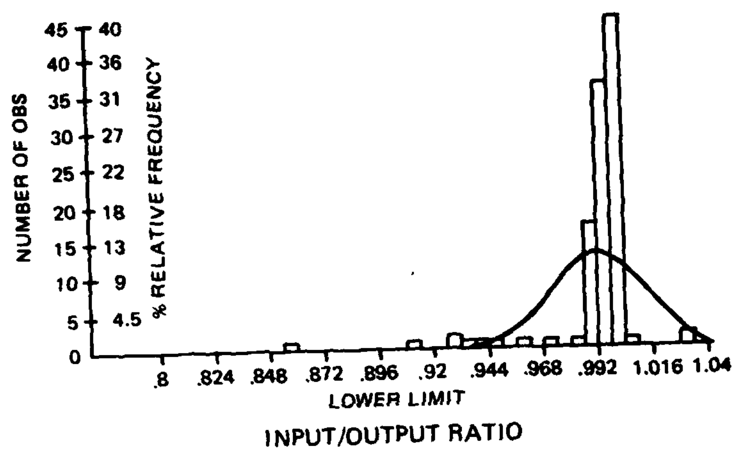
43. In the following material the upper and lower bounds on the value of the active arm resistance value allows examination of both extremes and observation of the behavior of the accelerometer under study.

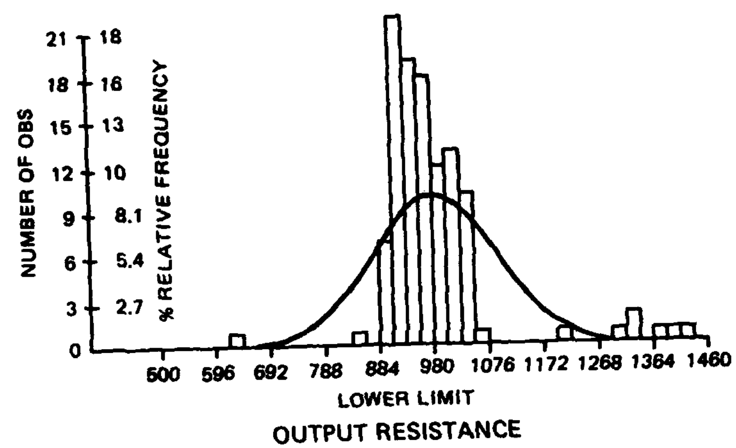
Distribution of Open Circuit Sensitivity

44. One histogram was calculated and plotted to find the distribution in the open circuit sensitivity S1 supplied by the manufacturer. One hundred and eleven 25-g accelerometers were used as a sample. From this histogram, the following is evident:

$6.5 \leq S_1 \leq 15.8$ mv/g in 98.2 percent of the accelerometers (Figure 25).

45. As a result of this study we conclude that accelerometers of this type have a large variability in characteristics. From this conclusion it is determined that calibrations should be measured by individual accelerometer parameters and should not be based on class assumptions.





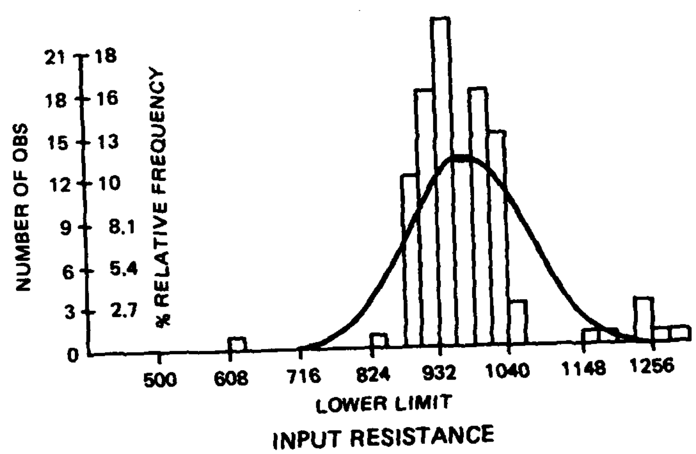


Figure 24. Histograms used to find active arm range

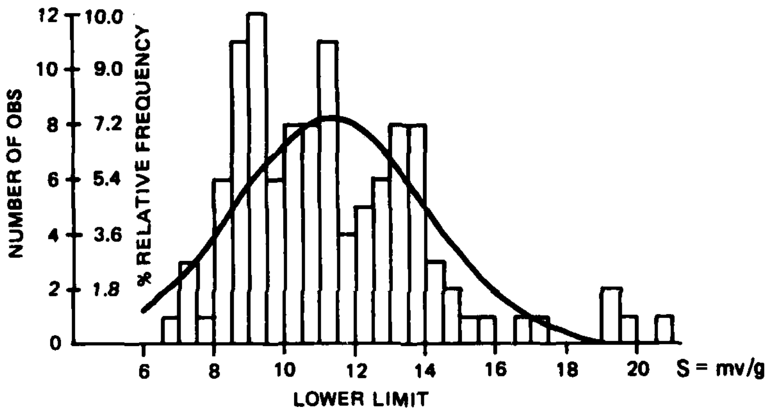


Figure 25. Histogram used to find distribution of S_1

PART IV: NETWORK ANALYSIS OF TRANSDUCER BRIDGE CIRCUIT NETWORK

Introduction

46. A well-founded study involving the static electric response of the measurement circuit must be based on the voltage and current status of each circuit element. Under given conditions these details are necessary for an accurate investigation. If complete information on the static electric response were available, studies could be conducted on the effect of a change in some part of the circuit. Such change might include the cable length, transducer-input (or output) resistance, and the signal-conditioning unit-input resistance. Complete understanding of the entire measurement circuit behavior allows for better measurement results.

Circuit Representation

47. A circuit schematic was drawn to represent the physical measurement of its elements. The framework includes:

- a. The transducer electrical resistance elements.
- b. Resistance elements representing the cable conductors used to connect excitation from the signal-conditioning unit to the transducer input terminals.
- c. Resistance elements representing the cable conductors used to connect the transducer output terminal signals to the signal-conditioning unit.
- d. Input resistance of the amplifier.
- e. Constant current source (or voltage) for transducer excitation.
- f. The calibration resistor used for electrical simulation of the physical input.

48. The "Tree-Cotree Technique" was used in writing network equations for the above circuit. In such equations the independent variable is the change in the gage resistance or the resistances of the wires or any branch in the circuit. The dependent variable is the voltage appearing across the input resistance of the amplifier (or the current through it).

49. Each of the circuit elements (except the excitation source) was represented by one or more resistances. A mathematical model was developed to

represent this circuit, and the final representation of the circuit was in matrix form. This was done for both kinds (voltage, current) of excitation.

50. Each matrix was used in the construction of a computer program in which each resistance in the circuit could be changed independently; this program gives the current or voltage in any branch of the circuit. A diagram representing the physical measurement circuit is shown in Figure 26.

Loop Equations

51. If the excitation used in the circuit is a constant voltage source and the balance potentiometer is assumed to have negligible effect, the following equations will be representative.

(I) (R6 + R1 + R2 + R10) + (II) (-R6) + (III) (-R1) + (IV) (-R1 - R2) = V

(I) (-R6) + (II) (R7 + R5 + R4 + R6) + (III) (-R5 - R4) + (IV) (-R4) = 0

(I) (-R1) + (II) (-R4 - R5) + (III) (R8 + R9 + R1 + R4 + R5) + (IV) (R1 + R4) = 0

(I) (-R1 - R2) + (II) (-R4) + (III) (R1 + R4) + (IV) (R1 + R4 + R3 + R2) = 0

where Rn (n = 1, 2, ., ., 9) represents the elements in the circuit and the excitation voltage is (V) volts. Complete derivation is in Appendix C.

52. If the excitation used in the circuit is a constant current and the balance potentiometer is assumed to be negligible, these equations will represent the circuit:

(I) (R7 + R9) + (II) (R6 + R7 + R5 + R4) + (III) (-R5 - R4) + (IV) (-R5) = 0

(I) (-R9) + (II) (-R4 - R5) + (III) (R8 + R9 + R5 + R1 + R4) + (IV) (R8 + R5 + R9) = 0

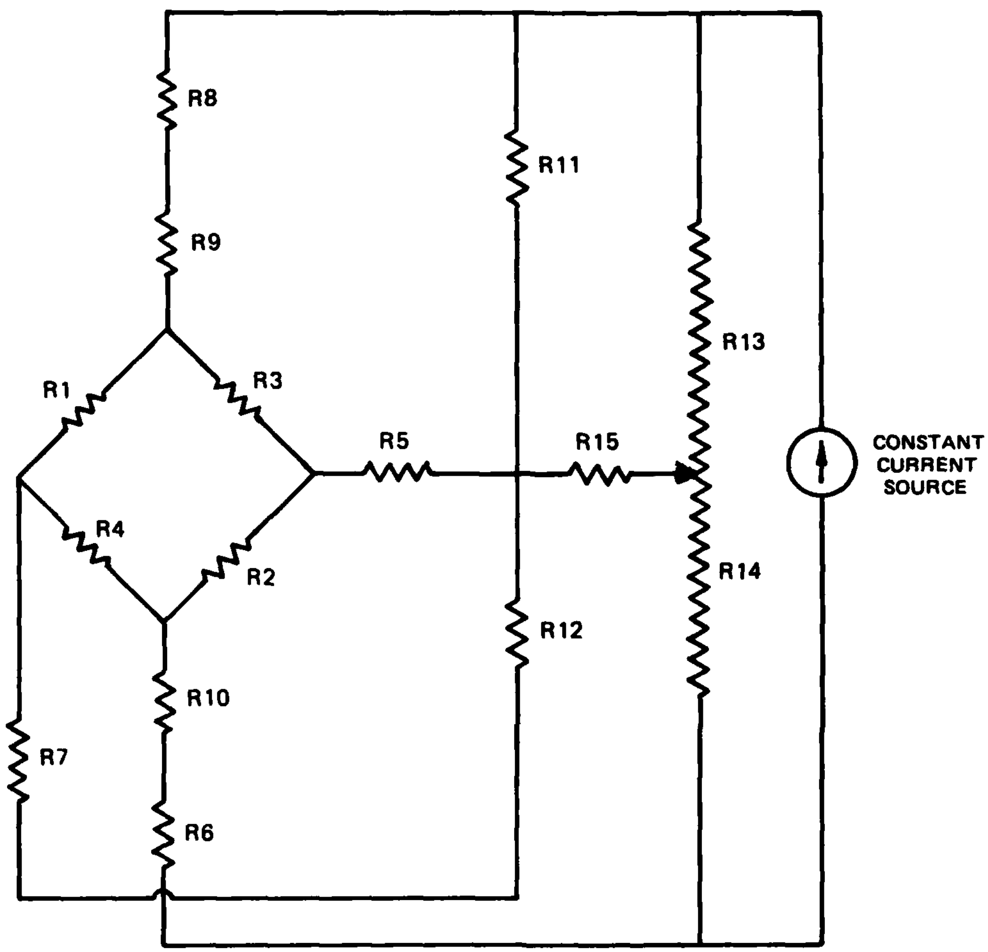
(I) (-R3 - R5) + (II) (-R5) + (III) (R8 + R9 + R5) + (IV) (R8 + R5 + R9 + R2 + R3) = 0

where Rn (n = 1, 2, , 9) represents the elements in the circuit, and the excitation current is (I) mA. Complete derivation is in Appendix D.

53. In the actual circuit of the measurement system (shown in Appendix E), a potentiometer is used to balance the bridge (i.e., the transducer) before taking any reading during calibration or measurement. When taking the potentiometer into consideration, the loop equations which represent the circuit will be as follows:

(I) (R2 + R4 + R1 + R3) + (II) (R4 + R1) + (III) (R1 + R3) + (IV) (R4 + R1 + R3) + (V) (-R3) + (VI) (-R3) = 0

(I) (R1 + R3) + (II) (R1) + (III) (R7 + R12 + R1 + R3 + R5) + (IV) (R1 + R3 + R5) + (V) (-R3 - R5) + (VI) (-R3 - R5) = 0



R1 TRANSDUCER BRIDGE RESISTANCE
R2 TRANSDUCER BRIDGE RESISTANCE
R3 TRANSDUCER BRIDGE RESISTANCE
R4 TRANSDUCER BRIDGE RESISTANCE
R9 TRANSDUCER BRIDGE RESISTANCE
R10 TRANSDUCER BRIDGE RESISTANCE

R5	CABLE RESISTANCE	; R11	CALIBRATION RESISTOR
R6	CABLE RESISTANCE	; R12	AMPLIFIER INPUT RESISTANCE
R7	CABLE RESISTANCE	; R13 + R14	POTENTIOMETER
R8	CABLE RESISTANCE	; R15	POTENTIOMETER ARM RESISTOR

Figure 26. The physical measurement circuit

(I) (R4 + R1 + R3) + (II) (R6 + R10 + R4 + R1) + (III) (R1 + R3 + R5)
+ (IV) (R14 + R6 + R10 + R4 + R1 + R3 + R5 + R15) + (V) (-R3 - R5)
+ (VI) (-R3 - R5 - R15) = 0

(I) (-R3) + (II) (R9 + R8) + (III) (-R5 - R3) + (IV) (-R5 - R3)
+ (V) (R11 + R5 + R3 + R9 + R8) + (VI) (R5 + R3 + R9 + R8) = 0

(I) (-R3) + (II) (R9 + R8) + (III) (-R5 - R3) + (IV) (-R15 - R5 - R3)
+ (V) (R5 + R3 + R9 + R8) + (VI) (R13 + R15 + R5 + R3 + R9 + R8) = 0

54. Since a constant current source is used for excitation in most of the blast phenomena tests, this configuration is the one with the greatest interest. For this reason, this derivation of loop equations was made on a circuit having a constant current source for excitation. Rn (n = 1, 2, ., ., 15) are the resistive elements in the circuit. Details are in Appendix F.

55. It is important to state that when neglecting the potentiometer element in paragraphs 51 and 52 little accuracy is lost, because the transducer bridge is balanced when it is manufactured. However, to be most accurate and to represent the measurement circuit with the closest fidelity, the circuit analysis given in paragraph 53 should be adopted.

Matrix Form of Equations

56. Loop equations in paragraph 51 are written in matrix form as the following:

$$[A]\ [X] = [B] \qquad \text{Matrix Equation (1)}$$

$$A = \begin{bmatrix} R6 + R1 + R2 + R10 & -R6 & -R1 & -R1 - R2 \\ -R6 & R7 + R5 + R4 + R6 & -R5 - R4 & -R4 \\ -R1 & -R4 - R5 & R8 + R9 + R1 + R4 + R5 & R1 + R4 \\ -R1 - R2 & -R4 & R1 + R4 & R1 + R4 + R3 + R2 \end{bmatrix}$$

$$X = \begin{bmatrix} I \\ II \\ III \\ IV \end{bmatrix} \qquad B = \begin{bmatrix} V \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad V = \text{excitation voltage}$$

57. Loop equations in paragraph 52 are written in matrix form as the following:

$$[A]\ [X] = [B] \qquad \text{Matrix Equation (2)}$$

$$A = \begin{bmatrix} R6 + R7 + R5 + R4 & -R5 - R4 & -R5 \\ -R5 - R4 & R8 + R9 + R5 + R1 + R4 & R8 + R5 + R9 \\ -R5 & R8 + R9 + R5 & R8 + R5 + R9 + R2 + R3 \end{bmatrix}$$

$$X = \begin{bmatrix} II \\ III \\ IV \end{bmatrix} \qquad B = \begin{bmatrix} -I\ (R7 + R9) \\ I\ (R9) \\ I(R3 + R5) \end{bmatrix} \qquad I = \text{excitation current}$$

58. Loop equations in paragraph 53 are written in Matrix form as follows:

$$[A]\ [X] = [B] \qquad \text{Matrix Equation (3)}$$

$$A = \begin{bmatrix} A11 & A12 & A13 & A14 & A15 \\ A21 & A22 & A23 & A24 & A25 \\ A31 & A32 & A33 & A34 & A35 \\ A41 & A42 & A43 & A44 & A45 \\ A51 & A52 & A53 & A54 & A55 \end{bmatrix} \quad X = \begin{bmatrix} X1 \\ X2 \\ X3 \\ X4 \\ X5 \end{bmatrix} \quad B = \begin{bmatrix} B1 \\ B2 \\ B3 \\ B4 \\ B5 \end{bmatrix}$$

where

A11 = R2 + R4 + R1 + R3
A12 = R1 + R3
A13 = R4 + R1 + R3
A14 = - R3
A15 = - R3

A21 = A12
A22 = R7 + R12 + R1 + R3 + R5
A23 = R1 + R3 + R5
A24 = - R3 - R5
A25 = - R3 - R5

A31 = A13	A41 = A14
A32 = A23	A42 = A24
A33 = R14 + R6 + R10 + R4 + R1 + R3 + R5 + R15	A43 = A34
A34 = - R3 - R5	A44 = R11 + R5 + R3 + R9 + R8
A35 = - R3 - R5 - R15	A45 = R5 + R3 + R9 + R8

A51 = A15

A52 = A25

A53 = A35

A54 = A45

A55 = R13 + R5 + R3 + R9 + R8 + R15

X1 = I	B1 = -II (R4 + R1)
X2 = III	B2 = -II (R1)
X3 = IV	B3 = -II (R6 + R10 + R4 + R1)
X4 = V	B4 = -II (R9 + R8)
X5 = VI	B5 = -II (R9 + R8)

II = excitation current

Effect of Cable Length on Calibration Resistor Equivalent Value

59. For each different length of cable between the transducer and the signal-conditioning unit, there will be a difference in amplitude in the measurement circuit's output signal resulting from switching in a given shunt calibration resistor, as shown in Figure 27. Cable length effect on cal-resistor equivalency, obviously, must be taken into account in the circuit calibration procedure. WES SOP, in the past, has used an algebric equation for taking this into account.

Effect of Transducer Bridge Resistance on Calibration Resistor Equivalent Value

60. The output signal, due to a given calibration resistor, will be different for different transducer bridge resistance, although for the same

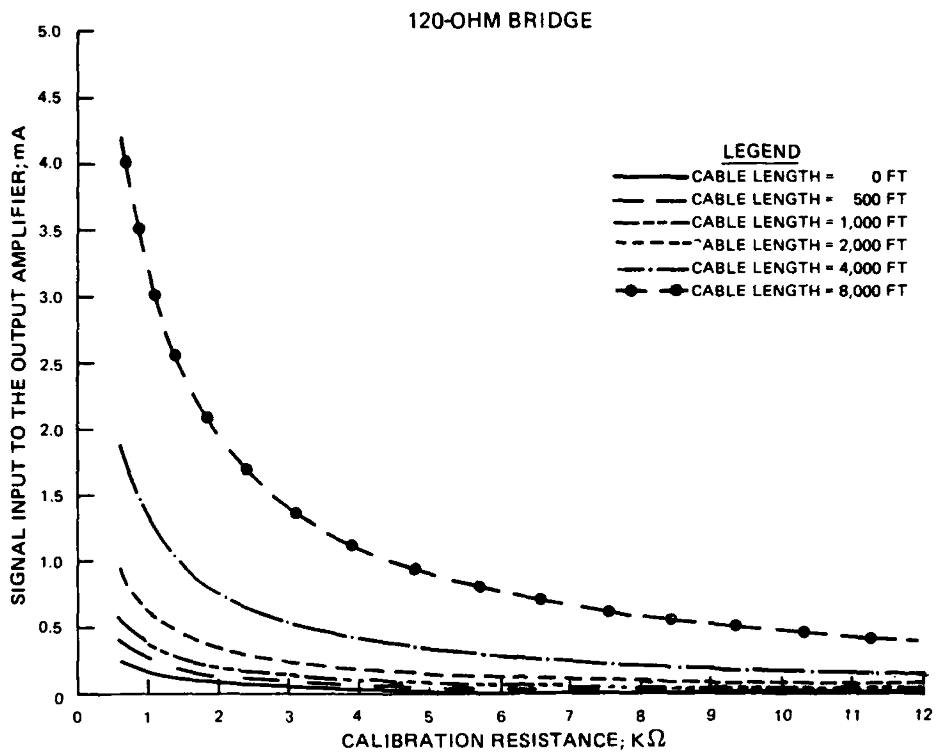
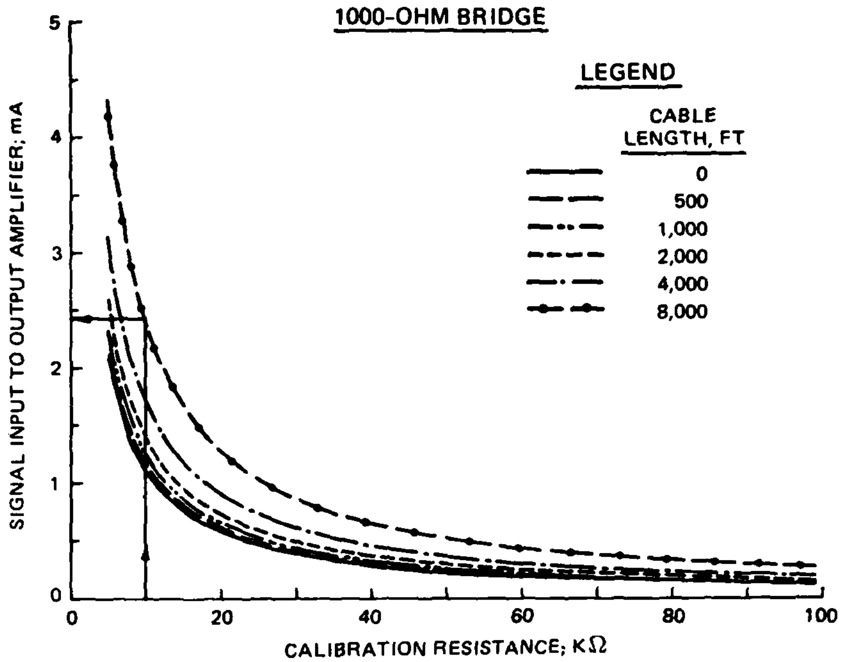


Figure 27. Different cable lengths in a measuring circuit and the corresponding output signal

length of cable running between the transducer and the signal-conditioning unit, as seen in Figure 28. It is also clear, from this same figure, that cable length effects are much more significant for transducers with low bridge resistance. There must be a compromise in selecting transducers because of conflicting effects (i.e., if a transducer with high bridge resistance is selected to minimize cable effect, this choice will result in having a system that is more susceptible to noise and has a lower frequency response than a low resistance bridge). Figure 28 is an example.

Effect of Signal-Conditioning Unit Amplifier Input Resistance on Calibration Resistor Value

61. As the signal-conditioning amplifier input resistance increases the output signal, due to a given value of the calibration resistor, decreases. This relation is nonlinear. As the value of the signal-conditioning amplifier



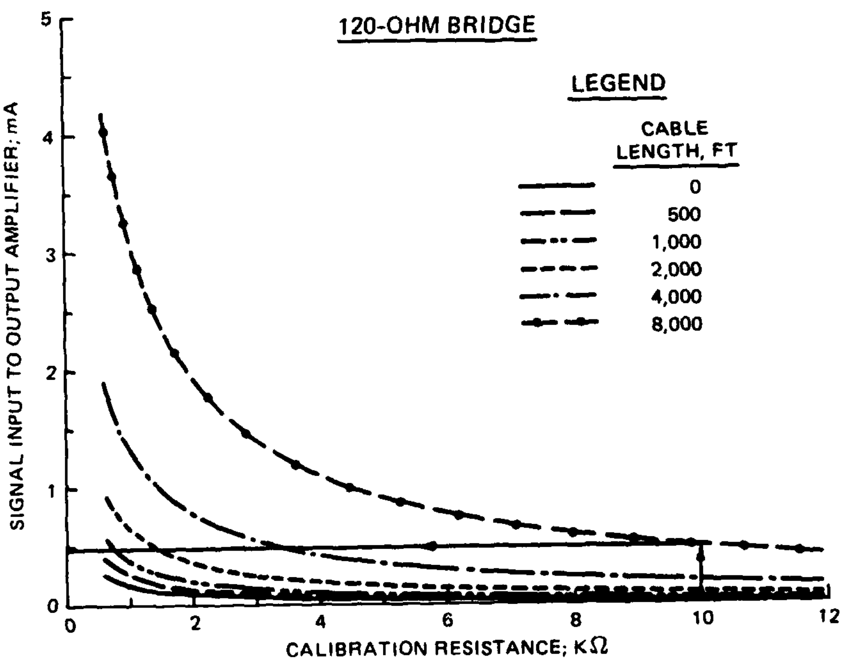


Figure 28. Comparison of transducer bridges

input resistance becomes very large, its effect on the calibration resistor becomes negligible. ISD normally uses a 2kΩ input resistance amplifier in blast phenomena tests, and this is low enough that it must be taken into account in calibration calculations. This behavior is explained when the output voltage from the transducer is V_o due to the application of a given calibration resistor. Then, across the amplifier input resistor the relation $V_o = IR_{amp}$ should be valid. This relation means that $I \alpha 1/R_{amp}$ and this is exactly what the curves in Figure 29 show.

Effect of Signal-Conditioning Balance Circuit on the Calibration Resistor

62. The WES signal-conditioning unit (Figure 5) contains a potentiometer (total resistance is 50kΩ) used to balance the transducer bridge (i.e., with no input to the transducer the output voltage will be set to zero). A moving arm divides the total resistance of the potentiometer into two sections. One of the sections, R13 (Figure 31), will act as part of the bridge arm that the calibration resistor shunts.

63. If the length of cable between transducer and signal-conditioning unit is changed the moving arm of the potentiometer should be readjusted to again balance the measurement circuit. This step in the measurement procedure causes the value of R13 which shunts the bridge arm to have different values. As a result, a change in the cable length affects the value of the calibration resistor in two ways (i.e., the cal-resistor value and the bridge arm value).

64. To study the variation in the resistive value of R13 due to the change in cable length, a circuit was simulated that includes an arbitrarily chosen transducer with typical unbalanced output, a signal-conditioning unit, and a variable-length cable. Figure 30 shows the result of this observation. For a cable length changing from 0 ft up to 8,000 ft, the bounds on the value of R13 are:

$$25.21k\Omega \le R13 \le 25.33k\Omega$$

The lower bound on the value of R13 is with a cable length of zero and the upper bound value results with an 8,000-ft cable length.

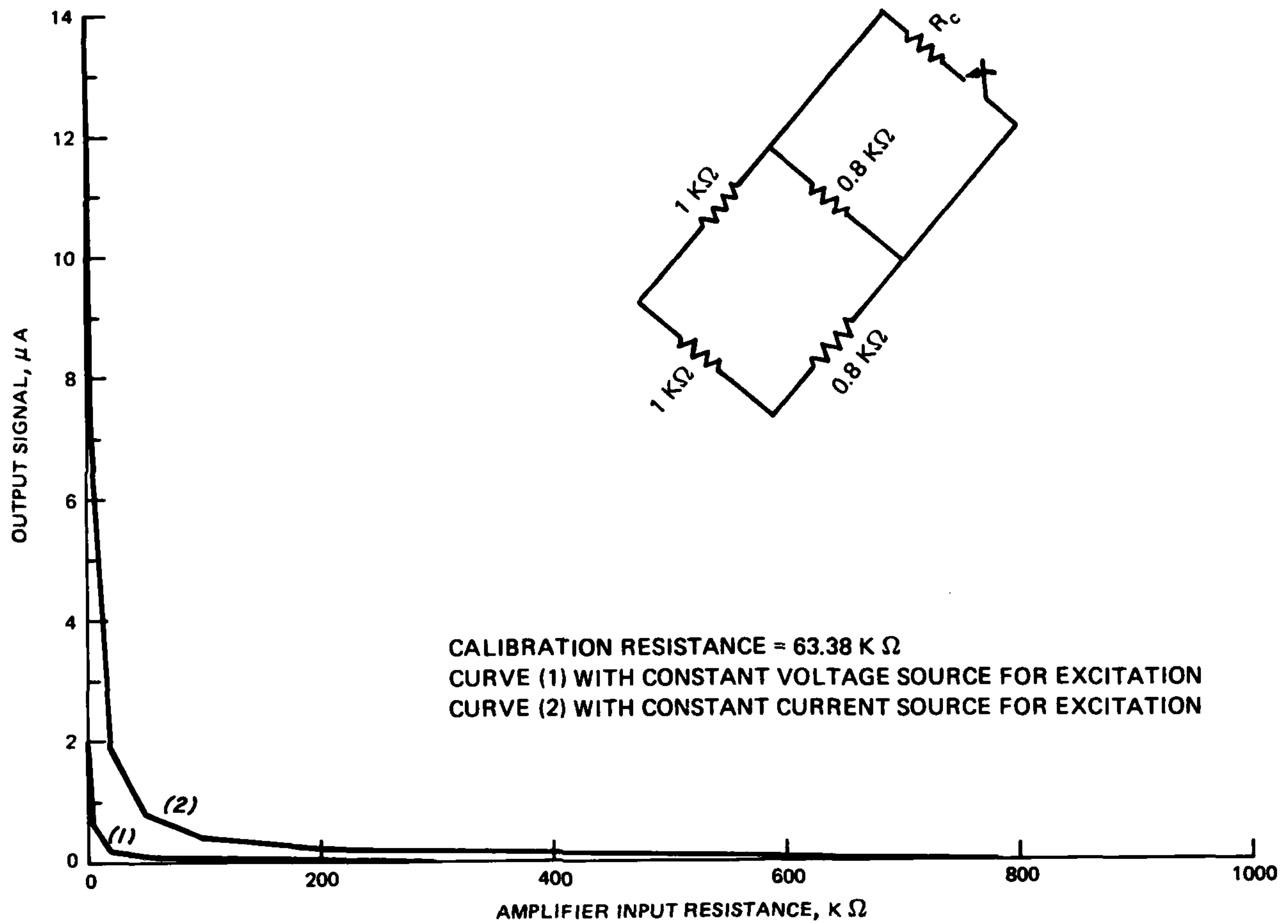


Figure 29. Amplifier input resistance versus output signal plot

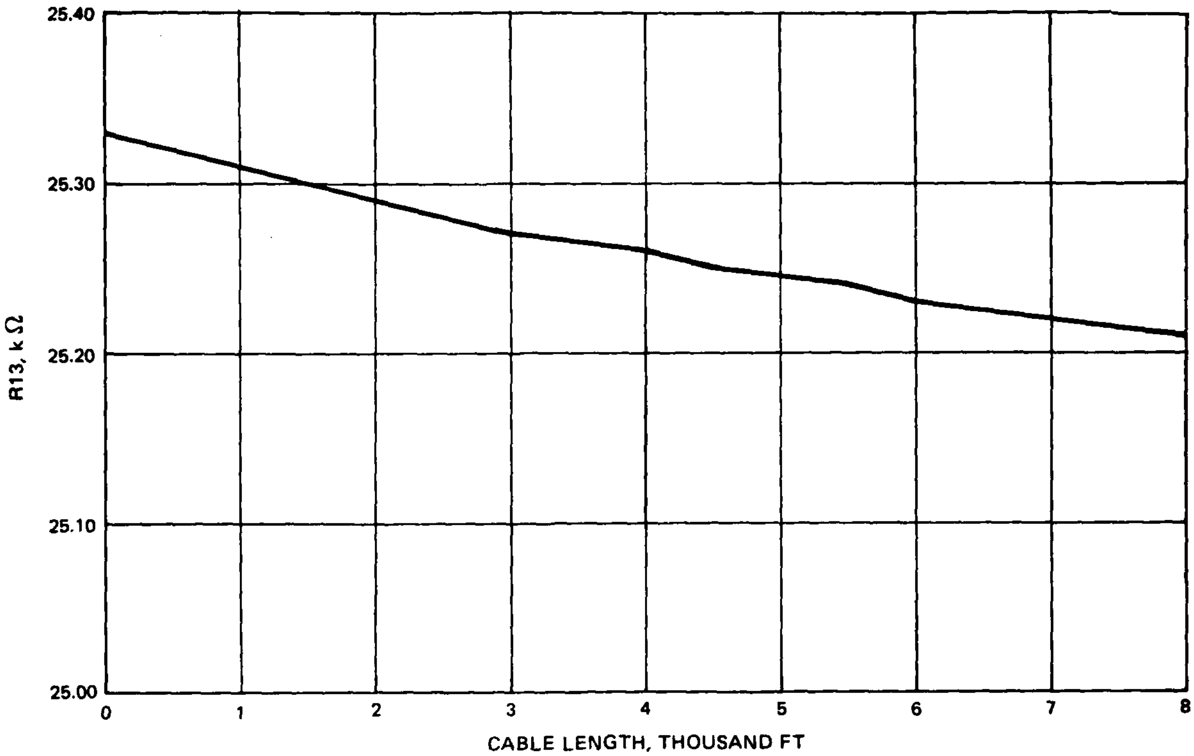


Figure 30. Variation in R12 resistive value due to the change in cable length in the case under study. (R13 is one of two resistive parts of the potentiometer which shunts the calibration resistor)

65. In Figure 31 all the elements of the measurement circuit are represented, with the exception of the excitation source. The calibration resistor is switched into the circuit at nodes a and b.

66. The equivalent resistance of the measurement circuit with which the calibration resistor will be confronted is a variable resistance. The value of this variable resistance changes each time a new length of cable is introduced into the circuit (i.e., changing R5, R6, R7, and R8 resistive value). This variation is not due just to the changes in the value of cable resistance, but also to the changes in R13 and R14, as changes in R13 and R14 values are essential for rebalancing the measurement circuit.

Effect of Transducer Bridge Unsymmetry

67. In Figure 32 the excitation current = 1mA. When R1 = R2 = R3 = R4 the transducer bridge is considered to be symmetric. With 500 ft of cable in the circuit and the calibration resistor equal to 10.7 kΩ and R1 = 1kΩ the

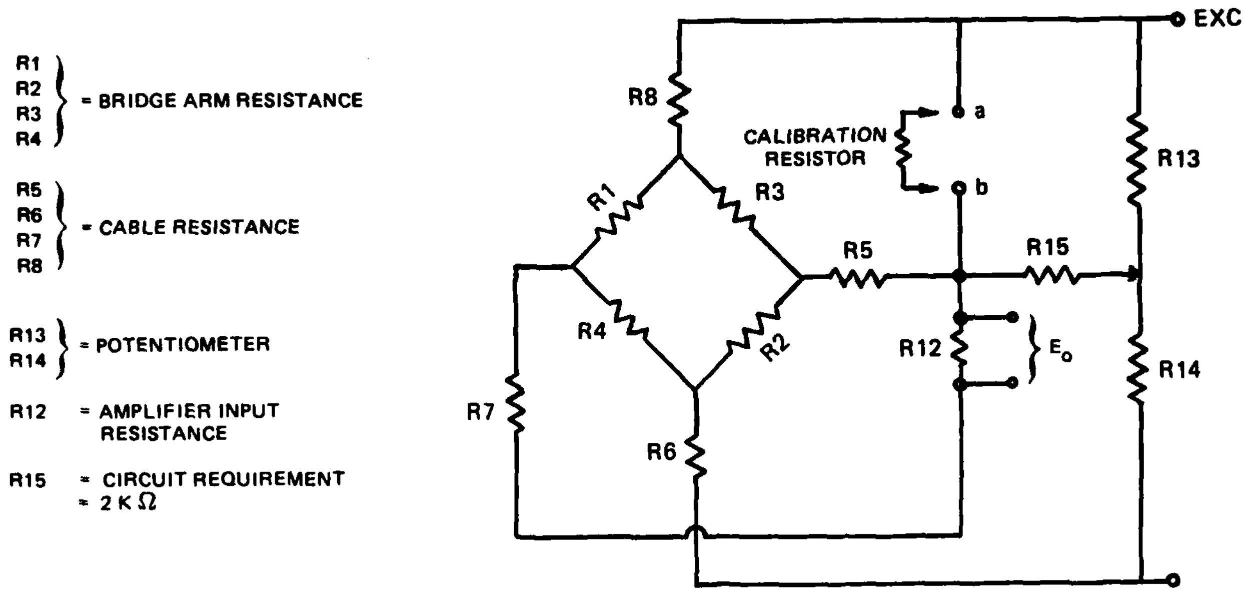


Figure 31. Measurement circuit representation--no excitation is shown

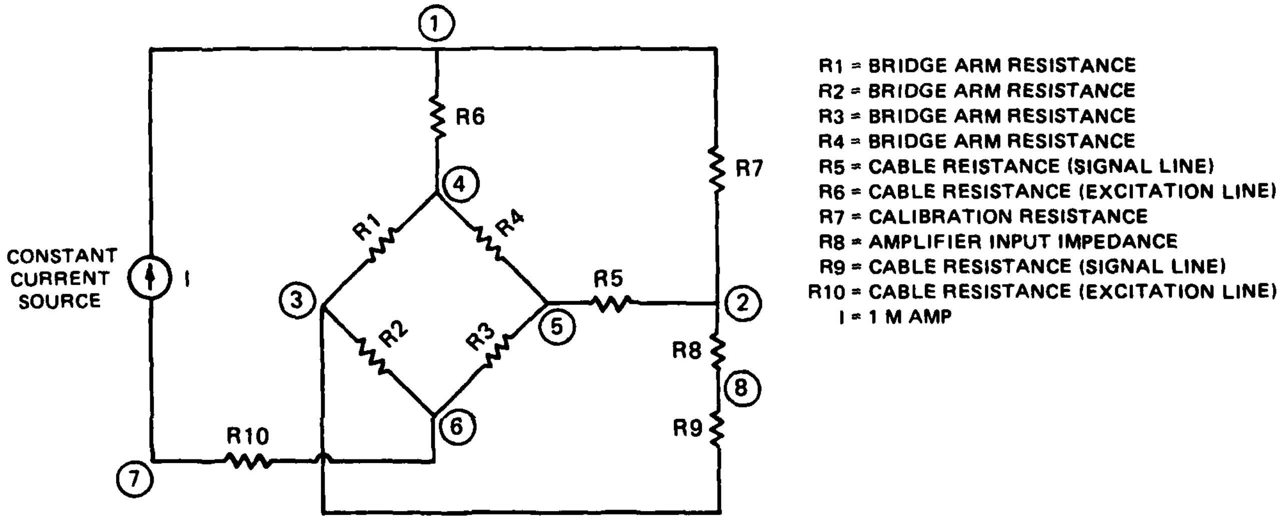


Figure 32. Transducer analysis circuit

output signal was 1.106 microamperes. When the symmetric bridge was changed to an unsymmetric bridge by varying the value of R1 and R2 and keeping the relation R1 = R2 = X and R3 = R4 = 1kΩ valid, the output signal changed as follows:

X in kΩ	Output Signal in μAmp
0.462	0.7266
1.50323	1.3
2.202	1.453

Sensitivity of the measurement circuit is affected by a change in the symmetry condition of the transducer bridge but the final measurement data are independent of the sensitivity of the measurement circuit due to circuit calibration.

Effect of Transducer Nonlinearity

68. For many transducers the mechanical response is close enough to linear that a linear curve fit is adequate, but occasionally a power curve fit could give better results. In either case the curve fitting can be done easily with the aid of the computer, and some of the information could be used to compute the value of the calibration resistor corresponding to the predicted amount of physical input.

Physical Circuit Validation of the Mathematical Model

69. Results computed from the matrix equation representing a bridge-type measurement circuit shown in Figure 33 were compared with values from a simulated bridge circuit built in the laboratory. These results are stated in Table 2. A comparison was made for several sets of widely different conditions. It is clear that the difference between the measured and the calculated values is negligible, making it reasonably certain that the mathematical model is correct in all aspects.

Calibration Room Data

70. Data collected in the calibration room provide information on the relation between a shunt calibration resistor and a physical input to the transducer. Calibration room data are taken with a very short, 2-ft cable

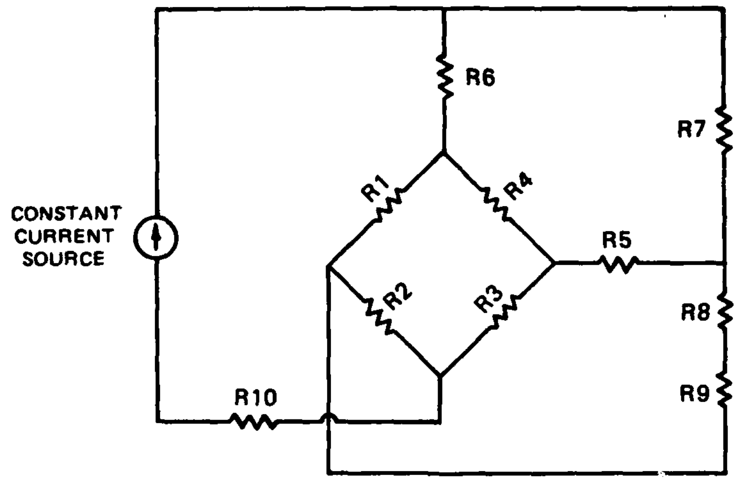


Figure 33. One physical representation of the transducer measurement circuit.

between the transducer and signal-conditioning unit. This short length of cable has so little effect on the circuit that it is completely negligible in the circuit analysis. In subsequent sections a transducer to signal-conditioner cable with negligible length is referred to as zero cable. In field use the transducer is typically several thousand feet from the signal-conditioning unit. Calibration-room data taken with zero cable length must be adjusted to represent actual field conditions at the test site. Both the computer-aided circuit analysis (CACA) and the standard operating procedure (SOP) can be used to compute the effect of cable length. To determine the validity and accuracy of the new CACA for calculating cable effects it was necessary to make a series of measurements under carefully controlled conditions. A complete strain-gage bridge-measurement circuit was set up in the WES blast phenomena calibration room. This experimental setup included a precision pressure source, a pressure transducer, a signal-conditioning unit, a precision digital voltmeter, and two cables to connect the transducer to the signal-conditioning unit. The two cables were the same type, although one was 2 ft long and the other was 4,000 ft long. The steps taken to collect cable-effect data were the following:

a. The signal-conditioning unit was balanced with the short cable connected and no pressure applied. Output voltage is zero under this condition.

b. A known pressure was applied to the pressure transducer and the pressure and output voltage were recorded.

c. The pressure was removed.

d. A defined arm in the pressure transducer was shunted with a known value calibration resistor. The resistor value was selected to give an output voltage near the voltage produced in step b.

e. Resistor value and output voltage were recorded.

f. Steps b through e were repeated for five values of pressure, starting at 20 percent of full-scale range of the pressure transducer and continuing in 20 percent steps.

After completing the experiment described above with a very short cable, the transducer to signal-conditioner cable was replaced with one 4,000 ft long. The circuit was rebalanced and steps b through f were repeated with the long cable. The only difference in the physical arrangement of the circuit was the cable length with all calibration and read-out equipment the same for both sets of data. The temperature in the calibration room was constant. The time lag between the two sets of data was very short so that no long-term drift effects could occur. The zero-cable and 4,000-ft-cable data sets thus provide a direct measure of the effect of the cable length on shunt resistor calibration equivalent values. Table 3 summarizes these data.

Comparison of Cable-Length Calibrations

71. Zero-cable calibration-collected data were used to develop a new value for the calibration resistor. This value is equivalent to the predicted physical input to a transducer with a known length of cable inserted in the measurement circuit. This is the cable that connects the signal-conditioning unit and the transducer.

72. The CACA and the SOP methods approach this procedure in different ways. As a base for comparison, two types of transducers were selected and the following experiment was performed on each one.

a. A complete measurement circuit was constructed to include the transducer, excitation source, signal-conditioning unit, a digital multimeter, and a known length of cable.

b. With the measurement circuit balanced and the zero cable connecting the signal-conditioning unit and the transducer, a known physical input was applied to the transducer. The output voltage from the signal-conditioning unit was then recorded.

c. With the measurement circuit balanced and zero cable between the signal-conditioning unit and the transducer, a selected

calibration resistor value was switched into the circuit to get the same output found in step b. This resistor is called RC1.

d. A 4,000-ft length of cable was connected between the transducer and the signal-conditioning unit, and the measurement circuit was balanced. The same physical input used in step b was again applied to the transducer, and the output voltage was recorded.

e. With circuit conditions the same as in step d, different known precision calibration resistors were switched into the circuit until the signal-conditioning unit output was the same as in step d, this resistor being called RC2.

f. The value of the calibration resistor found in step e (i.e., RC2) was considered to be equivalent to the physical input used in step b with the 4,000-ft cable in the measurement circuits.

73. In any field-site measurement of blast phenomena, the RC2 value is important since it is the reference on which the measured signal is evaluated.

PART V: QUESTIONS FROM THE DATA USER AND CORRESPONDING ANSWERS

KULITE and ENDEVCO Gages

74. At the time this analysis was conducted, KULITE gages were not available at WES. ENDEVCO gages were used, instead, due to the similarity to kulite in their electrical function. Each question asked below refers to KULITE gages, but due to these conditions all answers are for ENDEVCO gages. The answers are general enough, however, to satisfy the needs of this part of the report.

What quality control does ENDEVCO have

75. Each transducer is accompanied by a calibration certificate. On these certificates the following are documented:

- a. Transducer range in g.
- b. Excitation in dc volts.
- c. Sensitivity (open circuit) in mv/g.
- d. Zero measurement output in mv.
- e. Input resistance in ohms.
- f. Output resistance in ohms.
- g. Resonance frequency in kHz.
- h. Maximum transverse sensitivity (unitless).

All this is verified, directly or indirectly, in the calibration laboratory at WES.

Do we monitor ENDEVCO

76. Yes, 100 percent of the transducers used in WES blast phenomena are calibrated regardless of the manufacturer's identity. We do not normally make comparisons between WES and manufacturer's calibration data.

How unique is C_a? Should gages have approximately the same calibration

77. Since any gage from one type (e.g., 25-g gages) is specified by its input resistance, output resistance, and its input/output ratio, then its calibration is unique.

Are the calibration formulas
correct for the current lab/field SOP

78. Yes, the current calibration formulas are adequate within the normal expected accuracies of the blast phenomena measurement. Detail of the current calibration formulas with their error limits are mentioned below:

$$S = \frac{1}{n} \sum_{1}^{n} \frac{g}{E} \tag{1}$$

$$K = \frac{1}{n} \sum_{1}^{n} E_o (R_g + R_c) \tag{2}$$

$$C_{a/o} = SK \tag{3}$$

$$C_a = C_{a/o} F_L \tag{4}$$

$$\text{Calibration constant} = \frac{C_a}{R_c + R_g} \tag{5}$$

where

S = gage sensitivity
$C_{a/o}$ = calibration factor based on zero cable length
C_a = calibration factor with field cable length installed
R_c = calibration resistor
R_g = constant
K = constant
F_L = cable length correction factor

S and K Factors Errors

Error in S

79. One source of error in this factor is the assumption of linearity when calculating the average (i.e., taking the arithmetic mean average). The

statistical analysis given in paragraph 39 showed that for 100 percent of the transducers under investigation the assumption of linearity introduced only a 0.96 percent maximum error to the value of S .

Error in K

80. One of the sources of error in the formula for calculating K is R_g . The value of R_g in the formula which represents K is calculated by using the equation below:

$$R_g = \frac{2R_{amp} * R_d + R_a * R_d}{4R_{amp} + 2R_a + 2R_d} \qquad (6)$$

This equation is derived from a circuit analysis using a constant voltage source for excitation, the value of R_g is independent of the value of the excitation voltage. (See derivation in Appendix G.) In equation 6:

R_{amp} = input resistance of the amplifier (typical value, 2 kΩ)
R_d = resistive value of one dummy arm
R_a = resistive value of one active arm

In order to find the range of R_g for 25-g type transducers, the following values were used:

R_{amp} = 2 kΩ typical value
R_d = 1 kΩ from the manufacturer manual
$R_{a_{min}}$ = 0.64 kΩ from the statistical analysis
$R_{a_{max}}$ = 1.28 kΩ from the statistical analysis. The range of R_g is established by the use of equation 6 as:

$0.4113 \le R_g \le 0.42$ kΩ (for constant voltage source used for excitation).

81. In this example, the percentage of error in K value due to the variation in R_g in a given range of R_c is calculated as:

$$K = (R_c + R_g)E_o$$

$$K_1 = (R_c + 0.4113)E_o$$

$$K_2 = (R_c + 0.42)E_o$$

K_1 and K_2 could be used to represent one value of K for a given calibration resistor. The ambiguity in K is due to the lower and the upper bounds on R_g. If K_2 is assumed to be correct (or K_1 could be assumed correct) then percentage error in $K = (K_2 - K_1/K_2) \times 100$.

$$\% \text{ error in } K = \frac{R_c E_o + 0.42E_o - R_c E_o - 0.4113E_o}{R_c E_o + 0.42E_o} \times 100$$

$$= \frac{0.77}{R_c + 0.42}$$

Figure 34 shows the variation in the percentage error in K over a defined range of the calibration resistor. The other source of error in K is the assumption of linearity when calculating the average value.

Error in "$C_{a/o}$"

82. Since this factor is the result of the product of the factors S and K, the percentage error introduced to it is the geometric mean of the square of the errors in S and K.* In the transducers under investigation the error in $C_{a/o}$ was between zero and 1.16 percent.

Should $E(R_g + R_c)$ be constant for a constant current source

83. Yes. This has been established from simple circuit analysis in Appendix G or H. This is for a given transducer type and a specific excitation current value.

We assume R_g contributes very little, but can it be an index as how good/bad a calibration is

84. No. R_g is not used in finding the sensitivity of the transducer under calibration (i.e., S). It is only a term used in equation 2 to make this formula complete. In equation 2 E is the output voltage from the transducer due to the application of the resistor R_c. Transducer sensitivity has essentially nothing to do with R_g value. Two transducers with

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* This due to the fact that the errors in K and S are uncorrelated.

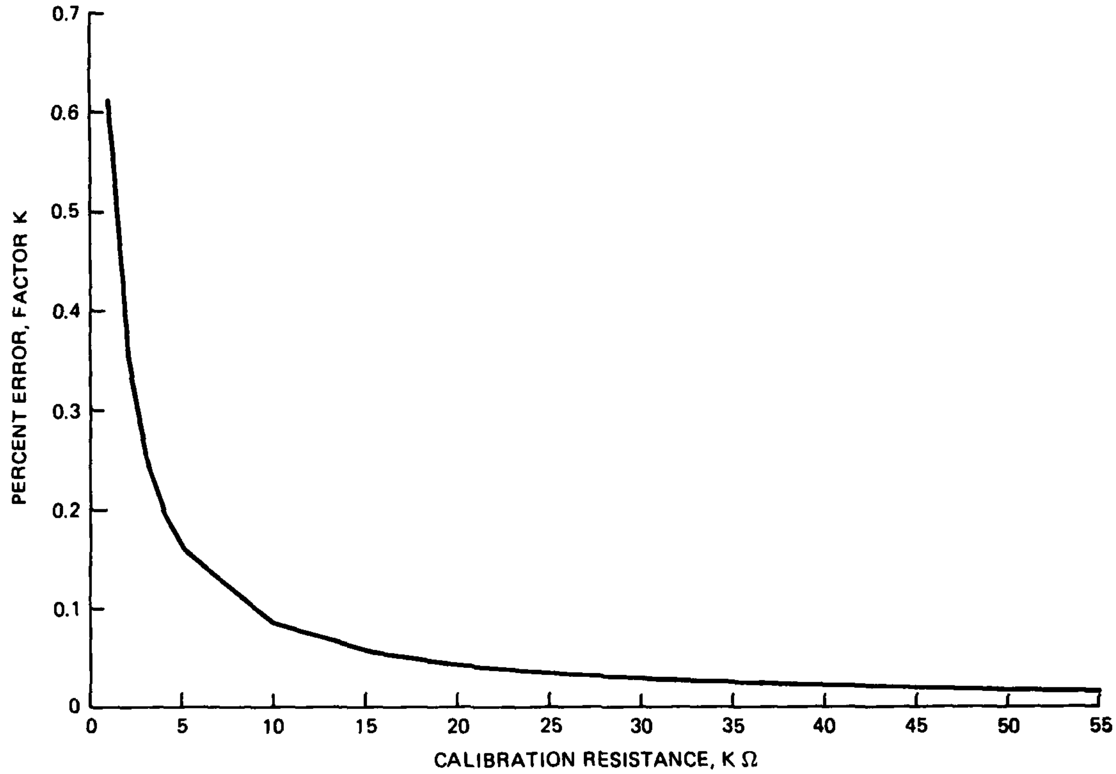


Figure 34. Percentage error in K values versus calibration resistor value

widely different R_g values can have the same sensitivity in terms of input and output functions.

What does R_g equal for constant current source, and should it equal f (gage, amp, cable resistance)

85. When a constant current source is used for excitation

$$R_g = \frac{2R_{amp} R_a R_d + R_{amp} R_d^2 + 2R_a^2 R_d}{2R_{amp} R_a + 2R_{amp} R_d + R_a^2 + R_d^2 \; 2R_a R_d}$$

From the above equation the reader will note that R_g is a function of R_{amp} , R_a , R_d . (For derivation, see Appendix H.)

How linear is the amplifier and the recording system? Are checks run

86. The static linearity of the amplifier is typically within

0.25 percent as measured in the WES laboratory. The static linearity of the magnetic tape recorder is specified by the manufacturer to be within 0.5 percent, and this is verified during maintenance checks. All of the new signal-conditioning units (i.e., the amplifiers) are checked for proper operation before they are released for use in the field or in the laboratory, and all signal-conditioning units are checked for proper operation prior to each blast phenomena test as part of the SOP procedure. The recording system as a whole (i.e., not each channel individually) is checked as far as the transient response is considered. This is done when the recording system is installed for a test measurement. Whenever a significant change in the recording system is made, then a complete system recheck is made.

How unique is C_a

87. C_a for a given transducer can give only one answer for the value of a calibration resistor equivalent to a given physical input to the transducer. Each transducer has its C_a value; different transducers have different C_a. C_a uniquely defines the relationship between the physical input to the transducer and the shunt resistor equivalent to it.

What is the approximate error from each of the following steps

88. Each step and its expected error is listed below:

a. Cable resistance: for analysis of the effect of cable resistance see paragraph 59.

b. Amplifier (signal-conditioning unit) input resistance: since the calibration and the measurement are done by using the same kind of amplifier, no error is introduced to the result of the measurement from this step.

c. $C_{a/o}$ = SK: see paragraph 78.

d. Recording system: tape speed accuracy is ±0.1 percent of selected tape speed. DC linearity is better than ±0.5 percent of peak-to-peak deviation referenced to best straight line.

e. Analog-to-digital conversion (A/D): sources of error in this procedure are:

- Linearity of the clock (sampling) - better than 0.01 percent
- Speed accuracy of the tape machine
- A/D module linearity - better than 0.1 percent (12-bit resolution)
- Noise from tape machine - see paragraph 15
- Noise from patch panel - less than 0.1 percent

89. Periodic tests are run to check the entire system. Before the digitizing procedure of each test, calibration is done for zero and 1 volt and almost at the same time the digitizing procedure is executed.

Can multi-cal steps be used and recorded

90. Yes, but this is not advised since this technique will not improve the digitization accuracy. Such accuracy could be improved by using the data interpolation procedure to represent the transducer response, see paragraph 68. A potential advantage is that the multi-cal step can be used to check the measurement system linearity, but this check is done by other means during system checkout rather than the use of multi-cal steps on the magnetic tapes.

Can all gages be calibrated the same way

91. No, but all gages are calibrated by the same basic technique. Obviously, accelerometers must have a different physical input from a pressure cell, etc. Transducers with a significantly nonlinear response should have equations used during data analysis different from those used for a transducer with good linearity.

PART VI: CACA AND SOP FOR COMPUTING THE CALIBRATION FACTOR

Standard Operating Procedure for Computing the Cal-Step Value

Procedure for computing
cal-step with zero cable

92. Transducers are calibrated in the laboratory at WES by effectively using zero cable length. From measurement data collected in the calibration laboratory the following steps are taken in computing the value of a recorded cal-step in engineering units.

a. Average sensitivity is calculated with the formula

$$S = \frac{1}{n} \sum_{1}^{n} EU/v \quad \text{Units are in EU/volt}$$

where

n = number of calibration points

EU = engineering unit input value

v = output voltage

b. Average value of shunt voltage constant K is calculated with the formula

$$K = \frac{1}{n} \sum_{1}^{n} (R_c + R_g)V \quad \text{Units are in k}\Omega\text{v}$$

where

n = number of calibration points

R_c = shunt calibration resistor value

R_g = gage constant

v = output voltage

c. The shunt calibration constant $C_{a/o}$ value is computed with the formula

$$C_{a/o} = SK \quad \text{Units are in } k_{\Omega} \text{ EU}$$

d. The calibration resistor value equivalent to a predicted engineering unit is calculated by the formula

$$RC_1 = \frac{C_{a/o}}{EU} - R_g \text{ Units are in k}\Omega$$

e. Calibration resistors are available only in discrete values such as 10 kΩ, 20 kΩ, . . .etc. Typically, a calibration resistor RC2 is selected from the discrete values available as close as possible in value to the resistance calculated in step d. The physical input equivalent in engineering units to this calibration resistor is then calculated using the formula:

$$EU = \frac{C_{a/o}}{RC_2 + R_g} \quad \text{Units are in engineering units}$$

Procedure for computing cal-
step values for installed transducers

93. In most field-site installations, long cables are used to connect the transducers to the signal-conditioning units. To allow for the effect of cable length in the measuring circuit, SOP uses the following steps to compute the value of a calibration resistor in equivalent engineering units.

a. Cable correction factor F_L is calculated with the formula:

$$F_L = \left(1 + \frac{2R_L}{R_x}\right)\left(1 + \frac{2R_L}{R_E}\right) \text{ unitless}$$

where

F_L = cable correlation factor

R_L = one-way cable resistance

R_E = transducer input resistance

R_x = see Appendix H for definition and evaluation of this term

b. The value of the calibration resistor equivalent to the predicted physical input to be measured is computed by the formula:

$$RC_1 = \frac{C_{a/o} \times F_L}{EU} - R_g \text{ Units are in k}\Omega$$

c. Calibration resistors are available only in discrete values such as 10 kΩ, 20 kΩ, ...etc. Typically, a calibration resistor RC2 is selected from the discrete values available as close as possible in value in the resistance calculated in step b. The physical input equivalent in engineering units to this calibration resistor is then calculated by using the formula:

$$EU = \frac{C_{a/o} \times F_L}{RC2 + Rg} \text{ Units are in engineering units}$$

Consequently, this calculated engineering unit is distinguished on the shot sheet as the cal-step value recorded on tape.

Computer-Aided Circuit Analysis Procedures

Procedure for computing cal-step with negligibly short cable (zero cable)

94. When a short or zero cable is used to connect the transducers to a signal-conditioning unit there are certain steps to follow:

a. Strain gage transducers are four terminal devices with six resistive values which could be measured as a result of different combination of these four terminals. Such six resistive values should be fed to the computer along with the type of the transducer.

b. Zero cable electro-mechanical calibration data of the transducer should be fed to the computer.

c. An interpolation method is used and two relations representing the electro-mechanical characteristic of the transducer measurement circuit will be available; such relations are in the form:

$$V_{out} = f(EU) \tag{7}$$

$$V_{out} = f(RC) \tag{8}$$

where

V_{out} = the output voltage

EU = the physical input to the transducer in engineering units

RC = calibration resistor in kΩ

d. Each element in the measurement circuit will be represented by one or more resistors, and each resistor will be assigned a definite value.

e. Equation 7 is used to compute the output voltage due to the application of the predicted input to be measured.

f. Equation 8 is used to compute the calibration resistive value equivalent to the application of the predicted physical input to be measured. The resistor will be RC1.

Procedure for computing cal-step value for installed transducers

95. A detailed circuit diagram for the steps below is shown in Appendix E, Figure E1.

a. From paragraph 94, step f calibration resistor RC1 is computed to be equivalent to the predicted physical input with zero cable between the transducer and the signal-conditioning unit.

b. RC1 in parallel with a defined arm in the transducer bridge R3 will have a resultant resistive combination, such combination is designated by R3//RC1. The difference between the two values is: R3 - (R3//RC1) = ΔR3.

c. In the mathematical model with the cable in the circuit and RC1 removed, the change ΔR3 in the resistive value of R3 will produce an input current to the amplifier. This current will be I1.

d. With the cable represented in the mathematical model, I1 is produced in the amplifier by shunting R3 by a calibration resistor RC2.

e. If, for obvious reasons, RC2 should be changed to RC3 (RC3 is selected as the nearest available resistance to RC2), then in the mathematical model with the cable represented the input current in the amplifier will no longer be I1. This current will be I2.

f. With RC3 removed and the cable still represented in the mathematical model, R3 is changed to a value that will make the input current in the amplifier equal to I2.

g. The value of R3 in step f is considered as a parallel combination of the original value of R3 and a value of the calibration resistor to be calculated.

h. Using the result from step g in equations 7 and 8 in paragraph 94, step c will give a value of a physical input equivalent to RC3.

PART VII: CONCLUSIONS AND RECOMMENDATIONS

96. The mathematical model mentioned in paragraph 53 gives an accurate picture of the static electrical response of the transducer bridge circuit represented. A computer program using this mathematical model generated results that agreed very closely with results obtained from measurements on an actual circuit. This mathematical model can be used to examine the static response of the transducer bridge circuit in greater detail and over a wider range of values than would be practical if empirical techniques were used.

97. Approximately 90 to 95 percent of WES blast phenomena measurements are made with system configuration (a) in Figure 3. Computation of the shunt calibration value equivalent to the physical input being measured is performed in different ways by using CACA and SOP. CACA requires the zero cable calibration data, the resistive value of six combinations associated with a four-terminal transducer, and the cable length. SOP requires the zero cable calibration data and the cable length.

98. Comparison between manufacturer (ENDEVCO) and WES calibrations showed that the zero cable calibration of WES is valid and is consistent with that of the manufacturer, and that the type of gages by WES are considered satisfactory for the blast phenomena measurement. Analysis of calibration errors proved them negligible due to variation in electrical resistance of the transducer bridge circuit elements.

99. Data reduction errors due to transducer nonlinearity are not significant for the commercial transducer types examined in this study and used by WES in blast phenomena measurement. There are still other types of nonlinear transducers used by WES in blast phenomena measurements that were not examined in this report. Nonlinearity does not degrade the accuracy of the electrical network mathematical model.

100. The mathematical model and the steps mentioned in paragraph 94 could be readily merged into the data processing portion of our blast phenomena measurement organization. Transducer nonlinearity and the shunt calibration resistor equivalency with a known length of cable in the circuit could be handled automatically.

101. This study does not include the electric transient response analysis of the transducer bridge circuit. An extension of this investigation to include the electric transient response is necessary.

102. It would be logistically impractical to calibrate each transducer in the laboratory with the cable length that will be used in the field.

103. Current laboratory calibration procedures for commercial transducers are considered adequate.

104. The current WES measurement methods are considered adequate, but some improvement in accuracy can be achieved in the data reduction phase. This can be accomplished by using nonlinear transducer response curves and the CACA, described earlier in this report.

105. Accuracy in the complete measurement procedure may also be improved by using the CACA method. This may be applied in one or more phases of the measurement procedure. Accuracy is required, for instance, in the stage where a physical input in the engineering unit is computed to be equivalent to a given calibration resistor in kΩ with a given length of cable running between the transducer and the signal-conditioning unit. This process will require the use of a computer at WES, where a program representing the CACA method is stored and can be run.

106. While the steady-state analysis conducted in this study is considered adequate and sufficient to answer the questions asked by the Structures Laboratory (SL) Group, it is recommended that a transient analysis be conducted as soon as funds and time are available. Such an analysis will help to clear many of the uncertainties related to the measurement circuit and procedure.

Table 1

Frequency Response and Signal/Noise (rms/rms)

Tape Speed ips	Center Frequency kHz	(FA or LP)* Filter Response	S/N (dB)** FA
		IRIG Low Band	
120	108	DC-20 kHz	50
60	54	DC-10 kHz	49
30	27	DC-5 kHz	49
15	13.5	DC-2.5 kHz	48
7-1/2	6.75	DC-1.25 kHz	47
3-3/4	3.375	DC-0.625 kHz	44
1-7/8	1.688	DC-0.312 kHz	42
		IRIG Intermediate Band	
120	216	DC-40 kHz	49
60	108	DC-20 kHz	49
30	54	DC-10 kHz	48
15	27	DC-5 kHz	47
7-1/2	13.5	DC-2.5 kHz	46
3-3/4	6.75	DC-1.25 kHz	43
1-7/8	3.375	DC-0.0625 kHz	40
15/16	1.688	DC-0.312 kHz	39

(Continued)

* Flat Amplitude (FA) within 1 dB; Linear Phase (LP).

** 1 dB less with LP filters.

Table 1 (Concluded)

Tape Speed ips	Center Frequency kHz	(FA or LP)* Filter Response	S/N (dB)** FA
	IRIG Wide Band Group 1		
120	432	DC-80 kHz	46
60	216	DC-40 kHz	46
30	108	DC-20 kHz	45
15	54	DC-10 kHz	44
7-1/2	27	DC-5 kHz	42
3-3/4	13.5	DC-2.5 kHz	41
1-7/8	6.75	DC-1.25 kHz	38
15/16	3.38	DC-0.625 kHz	36

Table 2

Comparison Between Math Model and Measured Values

Resistor	Value in kΩ	Voltage Across Resistor in Volts	
		Measured	Calculated
R1	3.5	1.41	1.404
R2	3.5	1.52	1.54
R3	3.5	1.95	1.96
R4	3.5	0.98	0.984
R5	1.5	0.42	0.42
R6	1.5	1.03	1.024
R7	5	1.58	1.59
R8	20	0.78	0.78
R9	1.5	0.06	0.0583
R10	1.5	1.5	1.5

Table 3

Calibration Room Validation Data

Cable Length = 2 ft			Cable Length = 4,000 ft		
Cal-Resistor kohm	Equiv. psi	O/P Voltage Volts	Cal-Resistor kohm	Equiv. psi	O/P Voltage Volts
6.0	263.0	2.295	6.0	482.0	4.045
6.5	243.5	2.124	6.5	448.5	3.752
7.0	227.0	1.977	7.0	419.0	3.495
8.0	200.0	1.737	8.0	370.5	3.078
8.5	189.0	1.637	8.5	350.0	2.904
9.0	178.5	1.550	9.0	332.0	2.749
9.5	169.5	1.470	9.5	315.5	2.610
10.5	154.0	1.333	10.5	286.0	2.370
11.0	147.0	1.273	11.0	275.0	2.264
11.5	141.0	1.219	11.5	263.5	2.169
12.0	135.0	1.169	12.0	253.0	2.081
12.5	130.0	1.123	12.5	243.0	2.000
13.0	125.5	1.082	13.0	234.0	1.925
13.5	121.0	1.042	13.5	226.0	1.857
14.0	117.0	1.006	14.0	218.5	1.791
14.5	113.0	0.972	14.5	211.0	1.731
15.0	109.0	0.940	15.0	204.5	1.674
15.5	106.0	0.910	15.5	198.5	1.622
16.0	103.0	0.882	16.0	192.5	1.572
16.5	99.5	0.855	16.5	187.0	1.525
17.0	97.0	0.830	17.0	182.0	1.481

APPENDIX A: INSTRUMENTATION TYPE AND ACCURACY

Constant Current Source Used in the Measurement Circuit

1. The constant current source is designed at ISD and its circuit includes a three-terminal adjustable voltage regulator (manufactured by the National Semiconductor Company). The accuracy of this source is 2 percent.

Reference Pressure Gage Used in the Calibration Room

2. The referenced gage is a bourdon gage type manufactured by Heise, Newtown, Connecticut. The accuracy of this gage is ±0.1 percent of full scale.

Digital Multimeter Used in the Calibration Room

3. The digital multimeter is a fluke 8600 type manufactured by John Fluke Mfg. Co. The accuracy of this meter is 0.02 percent in 0.005 percent of the ranges 2,20 and 2,000.

APPENDIX B: CALCULATION FOR TRANSDUCER ACTIVE ARM

Bridge Circuit Equations

1. From the circuit shown in Figure B1 below, the following equations are derived.

$$\text{Input (I/P) resistance} = \frac{2R}{R + 1} \tag{B1}$$

$$\text{Output (O/P) resistance} = \frac{R + 1}{2} \tag{B2}$$

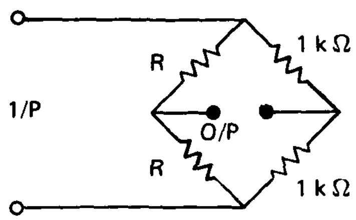


Figure B1. Bridge circuit presentation of the ENDEVCO transducer used in this analysis

Histogram Characteristics

Condition one

2. From the input and output resistance histograms shown in Figure 24, 97.3 percent of the transducers have the following characteristics:

a. Minimum output resistance = 820 Ω.

b. Maximum output resistance = 1140 Ω.

c. Minimum input resistance = 824 Ω.

d. Maximum input resistance = 1121 Ω.

3. Using Equations B1 and B2, the resistive active arm (R) values corresponding to the above-mentioned values are: 0.64 kΩ, 1.28 kΩ, 0.7007 kΩ, and 1.2753 kΩ.

Condition two

4. From input/output (I/O) ratio histograms illustrated in Figure 24, 95.5 percent of the transducers have the following characteristics:

a. Minimum I/O ratio = 0.962.

b. Maximum I/O ratio = 1.022

5. The resistive (R) values corresponding to the above-mentioned ratios are given in the two following equations:

$$R^2 - 2.1580042R + 1 = 0 \tag{B3}$$

$$R^2 - 1.9138943R + 1 = 0 \tag{B4}$$

From Equation B3

$$R = 0.6737\ k\Omega \text{ or } R = 1.4844\ k\Omega$$

From Equation B4

$$R = 0.9569\ k\Omega \text{ or } R = 0.9569\ k\Omega$$

6. As a result of the above calculations:

$$R_{min} = 0.64\ k\Omega$$

$$R_{max} = 1.28\ k\Omega$$

where

R = 1.4844 kΩ is not applicable, since it is required that the value of the active arm should satisfy both conditions

APPENDIX C: COMPLETE DERIVATION OF LOOP EQUATIONS FOR MEASUREMENT CIRCUIT WITH CONSTANT VOLTAGE SOURCE AND NO POTENTIOMETER

1. The loop equations of the circuit shown in Figure C1 are as follows:

<u>Loop I</u>

$$-10 + (R6)(I - II) + (R1)(I - III - IV) + (R2)(I - IV) + (R10)(I) = 0$$

<u>Loop II</u>

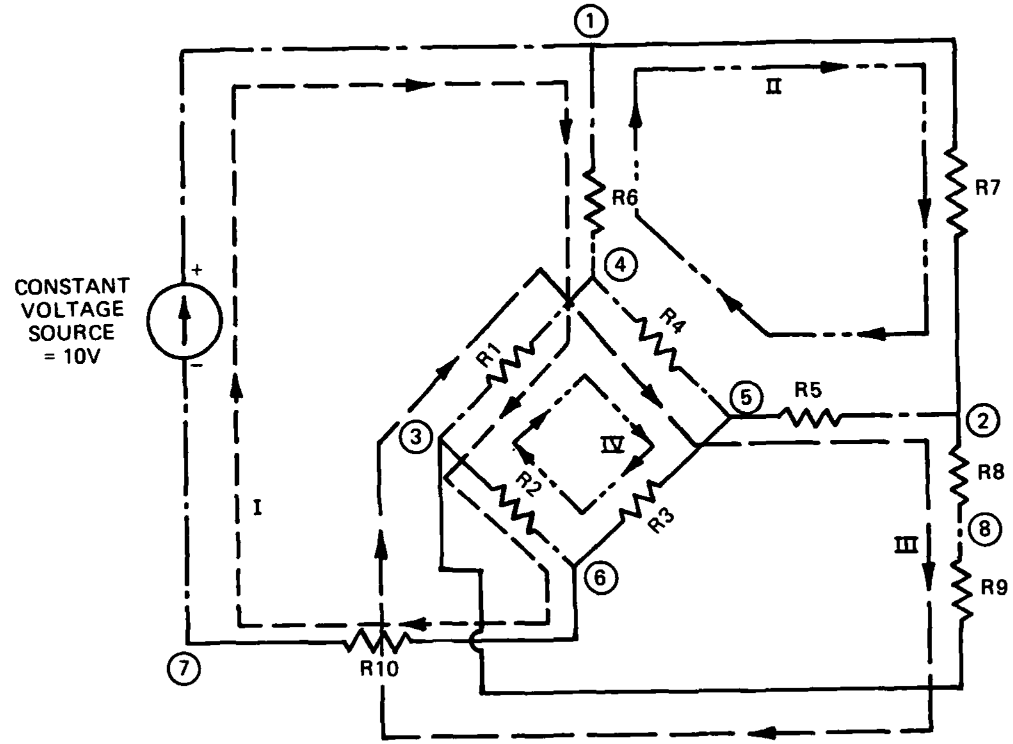
$$(R7)(II) + (R5)(II - III) + (R4)(II - III - IV) + (R6)(II - I) = 0$$

<u>Loop III</u>

$$(R8 + R9)(III) + (R1)(III - I + IV) + (R4)(III + IV - II) + (R5)(III - II) = 0$$

<u>Loop IV</u>

$$(R1)(IV - I + III) + (R4)(IV + III - II) + (R3)(IV) + (R2)(IV - I) = 0$$



R1 = BRIDGE ARM RESISTANCE
R2 = BRIDGE ARM RESISTANCE
R3 = BRIDGE ARM RESISTANCE
R4 = BRIDGE ARM RESISTANCE
R5 = CABLE RESISTANCE (SIGNAL LINE)
R6 = CABLE RESISTANCE (EXCITATION LINE)
R7 = CALIBRATION RESISTANCE
R8 = AMPLIFIER INPUT IMPEDANCE
R9 = CABLE RESISTANCE (SIGNAL LINE)
R10 = CABLE RESISTANCE (EXCITATION LINE)

Figure C1. Measurement circuit with constant voltage source and no potentiometer

APPENDIX D: COMPLETE DERIVATION OF LOOP EQUATIONS FOR MEASUREMENT CIRCUIT WITH CONSTANT CURRENT SOURCE AND NO POTENTIOMETER

1. The loop equations of the circuit shown in Figure D1 are as follows:

Loop I

$$(I)(R7 + R5 + R3 + R10) + (II)(R7 + R5) + (III)(-R5) + (IV)(-R5 - R3) = 0$$

Loop II

$$(I)(R5 + R7) + (II)(R4 + R5 + R6 + R7) + (III)(-R4 - R5) + (IV)(-R5) = 0$$

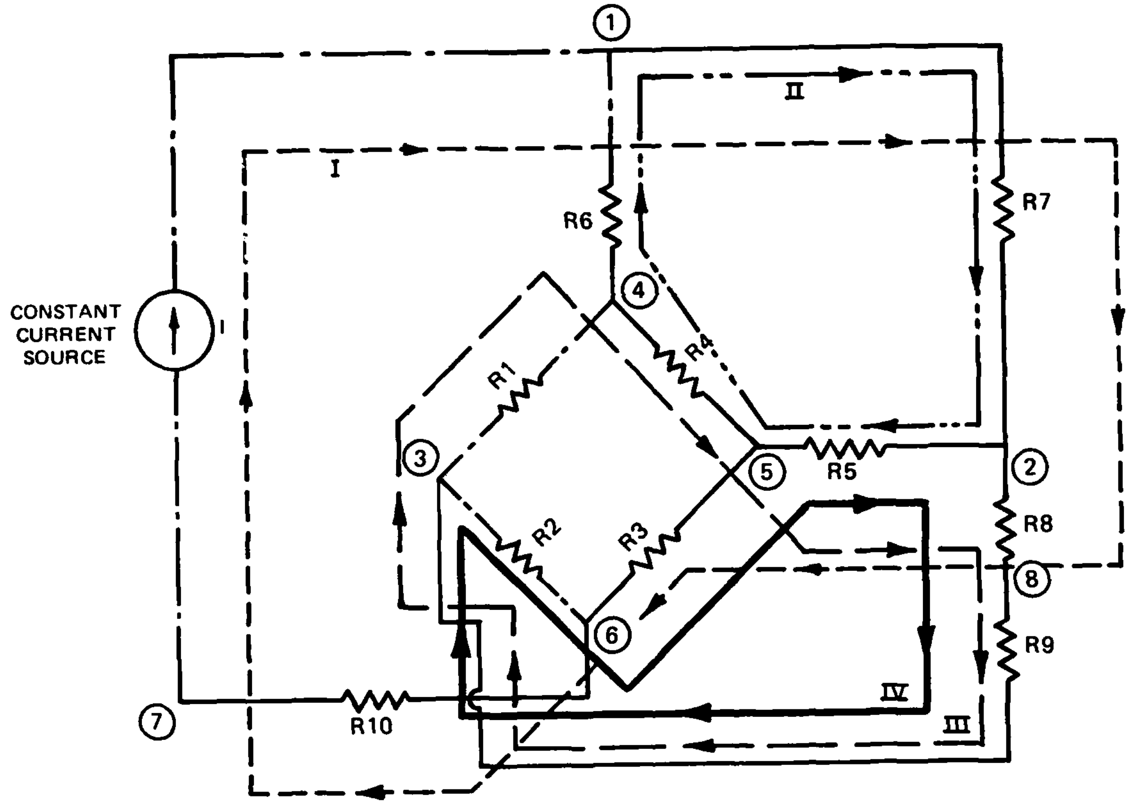
Loop III

$$(I)(-R5) + (II)(-R4 - R5) + (III)(R1 + R4 + R5 + R8 + R9) + (IV)(R5 + R8 + R9) = 0$$

Loop IV

$$(I)(-R3 - R5) + (II)(-R5) + (III)(R5 + R8 + R9) + (IV)(R2 + R3 + R5 + R8 + R9) = 0$$

Note: Due to the laws used in solving the above loop equations, Loop I should be discarded. The solution will be for three loop equations.



R1 = BRIDGE ARM RESISTANCE
R2 = BRIDGE ARM RESISTANCE
R3 = BRIDGE ARM RESISTANCE
R4 = BRIDGE ARM RESISTANCE
R5 = CABLE RESISTANCE (SIGNAL LINE)
R6 = CABLE RESISTANCE (EXCITATION LINE)
R7 = CALIBRATION RESISTANCE
R8 = AMPLIFIER INPUT IMPEDANCE
R9 = CABLE RESISTANCE (SIGNAL LINE)
R10 = CABLE RESISTANCE (EXCITATION LINE)
I = 1 m AMP

Figure D1. Measurement circuit with constant current source and no potentiometer

APPENDIX E: COMPLETE DERIVATION OF LOOP EQUATIONS FOR MEASUREMENT CIRCUIT WITH CONSTANT CURRENT SOURCE AND POTENTIOMETER

1. The loop equations of the circuit shown in Figure E1 are as follows:

Loop I

$$(I)(R1 + R2 + R3 + R4) + (II)(R1 + R4) + (III)(R1 + R3) + (IV)(R1 + R3 + R4) + (V)(-R3) + (VI)(-R3) = 0$$

Loop II

$$(I)(R1 + R4) + (II)(R1 + R8 + R9 + R6 + R10 + R4) + (III)(R1) + (IV)(R6 + R10 + R4 + R1) + (V)(R8 + R9) + (VI)(R8 + R9) = 0$$

Loop III

$$(I)(R1 + R3) + (II)(R1) + (III)(R1 + R3 + R5 + R7 + R12) + (IV)(R1 + R3 + R5) + (V)(-R3 - R5) + (VI)(-R3 - R5) = 0$$

Loop IV

$$(I)(R1 + R3 + R4) + (II)(R1 + R4 + R6 + R10) + (III)(R1 + R3 + R5) + (IV)(R1 + R3 + R4 + R5 + R6 + R10 + R14 + R15) + (V)(-R3 - R5) + (VI)(-R3 - R5 - R15) = 0$$

Loop V

$$(I)(-R3) + (II)(R8 + R9) + (III)(-R3 - R5) + (IV)(-R3 - R5) + (V)(R3 + R5 + R8 + R9 + R11) + (VI)(R3 + R5 + R8 + R9) = 0$$

Loop VI

$$(I)(-R3) + (II)(R8 + R9) + (III)(-R3 - R5) + (IV)(-R3 - R5 - R15) + (V)(R3 + R5 + R8 + R9) + (VI)(R3 + R5 + R8 + R9 + R13 + R15) = 0$$

Note: Due to the laws used in solving the above loop equations, Loop II should be discarded. The solution will be for five loop equations.

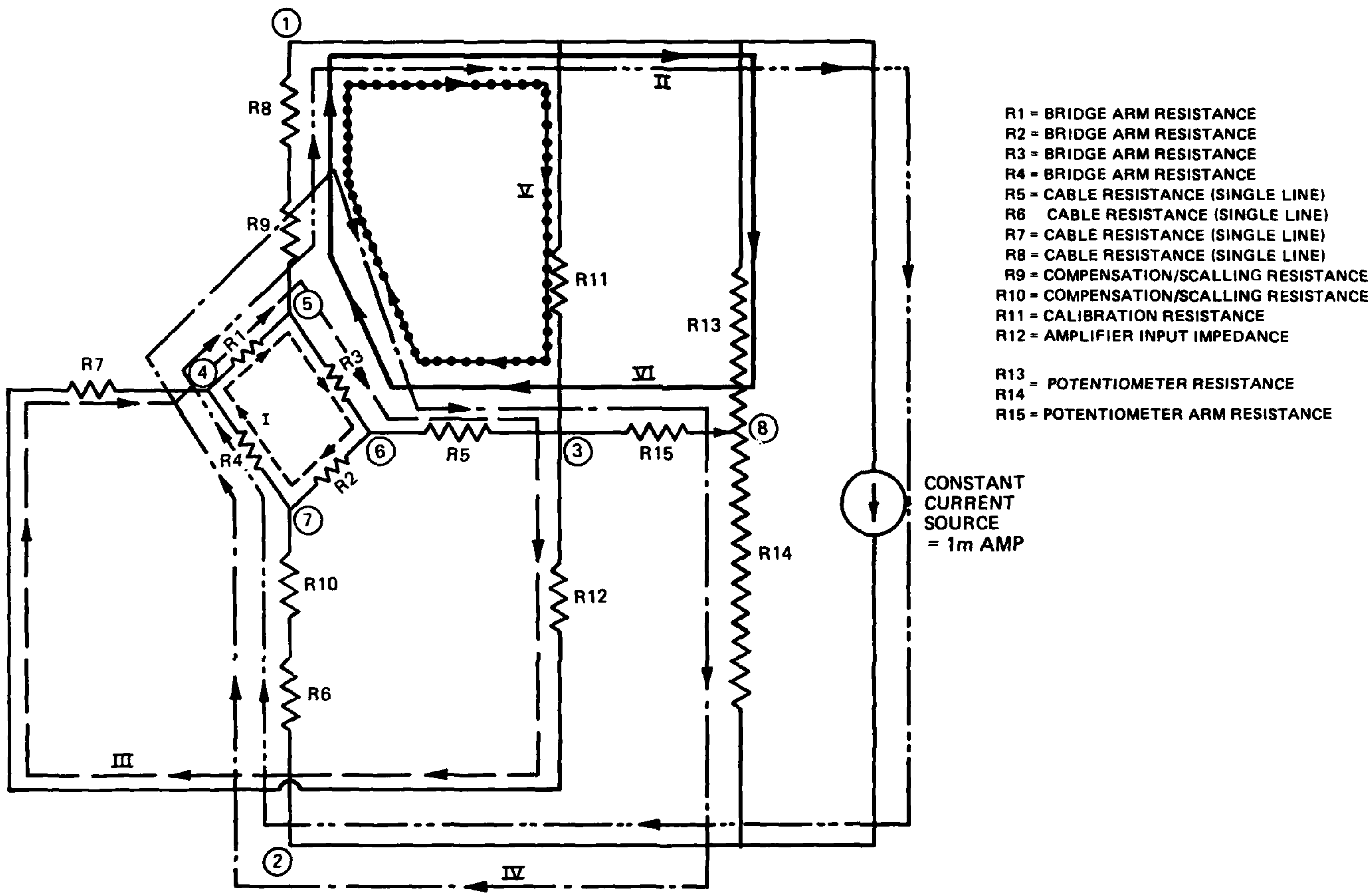
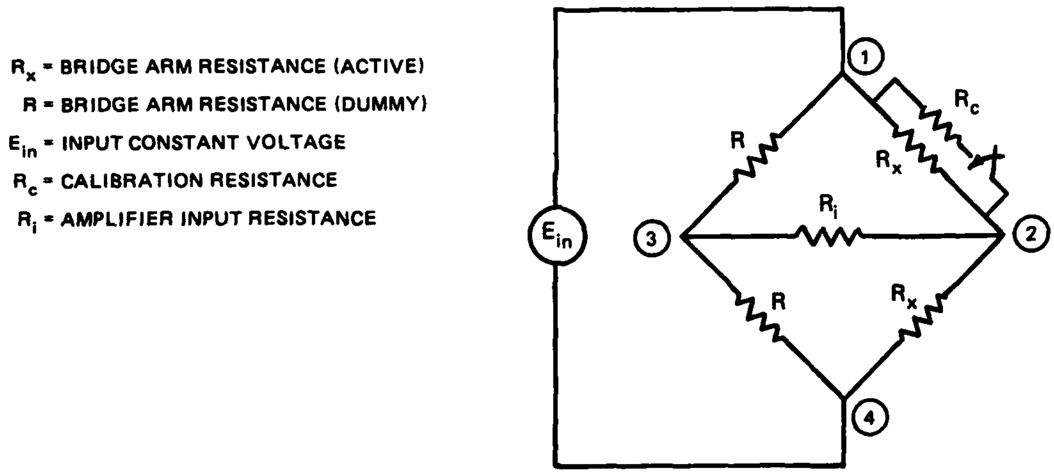


Figure E1. Measurement circuit with constant current source and potentiometer

APPENDIX F: DERIVATION OF Rg VALUE WITH CONSTANT VOLTAGE SOURCE USED FOR EXCITATION



1. The Thevenin's resistance (R_T) is the total resistance between nodes 2 and 3 with nodes 1 and 4 short-circuited in Figure F1.

$$R_T = \frac{R}{2} + \frac{\dfrac{R_x^2 R_c}{R_x + R_c}}{R_x + \dfrac{R_x R_c}{R_x + R_c}} = \frac{R}{2} + \frac{R_x^2 R_c}{R_x^2 + 2R_x R_c}$$

$$R_T = \frac{R}{2} + \frac{R_x R_c}{R_x + 2R_c}$$

2. To compute $E_{Thevenin}$ (E_T) the open circuit voltage between nodes 1 and 2 (E_{1-2}) should be computed as follows.

$$E_{1-2} = \frac{E_{in}}{2} - E_{in} \frac{\dfrac{R_x R_c}{R_c + R_x}}{\dfrac{R_x R_c}{R_c + R_x} + R_x}$$

$$= E_{in} \left(0.5 - \frac{R_x R_c}{2R_x R_c + R_x^2} \right)$$

$$= E_{in} \left(0.5 - \frac{R_c}{2R_c + R_x} \right) = E_{in} \left(\frac{R_c + 0.5R_x - R_c}{2R_c + R_x} \right)$$

$$= E_{in} \left(\frac{0.5R_x}{2R_c + R_x} \right)$$

3. The voltage (Ei) across the input resistance of the amplifier is computed from the circuit in Figure F2.

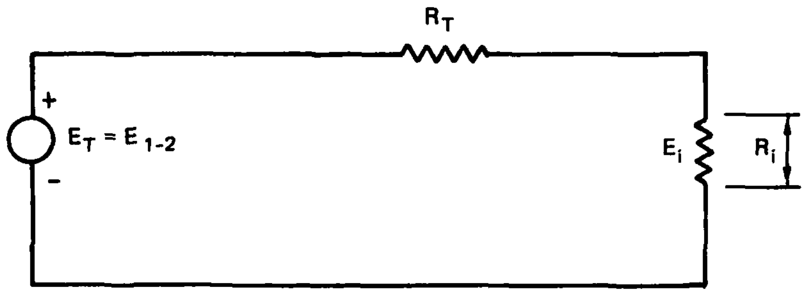


Figure F2

$$E_i = E_{in} \left(\frac{0.5\ R_x}{R_x + 2R_c} \right) \left(\frac{R_i}{R_i + \dfrac{R}{2} + \dfrac{R_x^2 R_c}{R_x^2 + 2R_x R_c}} \right)$$

$$E_i = E_{in} \left(R_i R_x^2 \right) \left(\frac{1}{2R_i R_x^2 + 4R_i R_x R_c + RR_x^2 + 2R_x R_c R + 2R_x^2 R_c} \right)$$

$$E_i\left(2R_i^2R_x + 4R_iR_xR_c + RR_x^2 + 2R_xR_cR + 2R_x^2R_c\right) = E_{in}\ R_iR_x^2$$

$$E_i\left(2R_iR_x + 4R_iR_c + RR_x + 2R_cR + 2R_xR_c\right) = E_{in}\ R_iR_x$$

$$E_i\left(R_c + \frac{2R_iR_x + RR_x}{4R_i + 2R + 2R_x}\right) = E_{in}\left(\frac{R_iR_x}{4R_i + 2R + 2R_x}\right)$$

$$E_i[R_c + R_g] = K$$

where

$$R_g = \frac{2R_iR_x + RR_x}{4R_i + 2R + 2R_x}\ ;\ K = E_{in}\left(\frac{R_iR_x}{4R_i + 2R + 2R_x}\right)$$

APPENDIX G: DERIVATION OF Rg VALUE WITH CONSTANT CURRENT SOURCE USED FOR EXCITATION

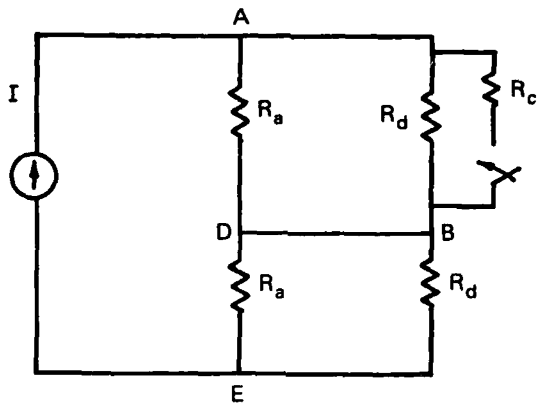


Figure G1.

1. The following derivations result from Figure G1:

$$E_{BE} = E_{AE}\left(\frac{R_d}{R_d + \frac{R_dR_c}{R_d + R_c}}\right) = E_{AE}\left[\frac{R_d}{\frac{R_d(R_d + R_c) + R_dR_c}{R_d + R_c}}\right]$$

$$E_{BE} = E_{AE}\,\frac{R_d(R_d + R_c)}{R_d(R_d + R_c) + R_cR_d}$$

$$E_{BD}\Big|_{o\,-\,c} = E_{BE} - E_{DE} = E_{AE}\left(\frac{R_d^2 + R_dR_c}{R_d^2 + 2R_dR_c}\right) - \frac{1}{2}\,E_{AE}$$

$$= E_{AE}\left(\frac{R_d^2 + R_dR_c}{R_d^2 + 2R_dR_c} - \frac{1}{2}\right) = E_{AE}\left[\frac{2R_d^2 + 2R_dR_c - R_d^2 - 2R_dR_c}{2\left(R_d^2 + 2R_dR_c\right)}\right]$$

$$E_{BD}\Big|_{o-c} = E_{AE}\left(\frac{R_d}{2R_d + 4R_c}\right)$$

But $E_{BD}\Big|_{o-c} = E_{Thevenin} = E_T$

$$E_T = E_{AE}\left(\frac{R_d}{2R_d + 4R_c}\right)$$

and

$$R_{AE} = \frac{(2R_a)\left(\dfrac{R_d^2 + 2R_dR_c}{R_d + R_c}\right)}{2R_a + \dfrac{R_d^2 + 2R_dR_c}{R_d + R_c}}$$

$$R_{AE} = \frac{2R_aR_d^2 + 4R_aR_dR_c}{2R_aR_d + 2R_aR_c + R_d^2 + 2R_dR_c}$$

$$E_T = I\left(\frac{2R_aR_d^2 + 4R_aR_dR_c}{2R_aR_d + 2R_aR_c + R_d^2 + 2R_dR_c}\right)\left(\frac{R_d}{2R_d + 4R_c}\right)$$

$$E_T = I\left[\frac{(R_aR_d)R_d}{2R_aR_d + 2R_aR_c + R_d^2 + 2R_dR_c}\right]$$

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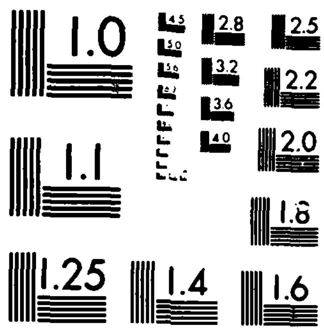

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

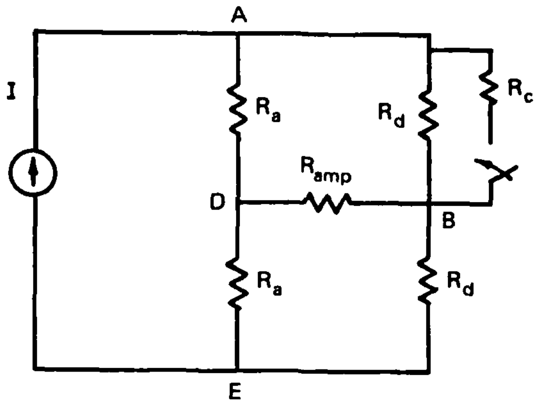

Figure G2.

2. From Figure G2 further derivations are:

$$R_{B-D}\Big|_{\text{source branch open}} = R_{\text{Thevenin}} = R_T$$

$$R_T = \frac{(R_a + R_d)\left(\dfrac{R_aR_d + R_aR_c + R_dR_c}{R_d + R_c}\right)}{\dfrac{R_aR_d + R_aR_c + R_dR_c + R_aR_d + R_aR_c + R_dR_c + R_d^2}{R_d + R_c}}$$

$$= \frac{R_a^2R_d + R_a^2R_c + R_aR_cR_d + R_aR_d^2 + R_aR_cR_d + R_d^2R_c}{2R_aR_d + 2R_aR_c + 2R_dR_c + R_d^2}$$

Figure G3.

3. Derivations from Figure G3 are:

$$E_i = E_T \left(\frac{R_{amp}}{R_{amp} + R_T} \right)$$

$$E_i = I \left(\frac{R_a R_d^2}{2R_a R_d + 2R_a R_c + 2R_d R_c + R_d^2} \right) \left(\frac{R_{amp}}{R_{amp} + \dfrac{R_a^2 R_d + R_a^2 R_c + R_a R_d^2 + R_c R_d^2 + 2R_a R_c R_d}{2R_a R_d + 2R_a R_c + 2R_d R_c + R_d^2}} \right)$$

$$E_i = I \left[\frac{R_a R_d^2 R_{amp}}{R_{amp} \left(2R_a R_d + 2R_a R_c + 2R_d R_c + R_d^2 \right) + R_a^2 R_d + R_a^2 R_c + R_a R_d^2 + R_c R_d^2 + 2R_a R_c R_d} \right]$$

$$E_i \left[R_c \left(2R_{amp} R_a + 2R_{amp} R_d + R_a^2 + R_d^2 + 2R_a R_d \right) + 2R_{amp} R_a R_d + R_{amp} R_d^2 + 2R_a^2 R_d \right]$$

$$= IR_a R_d^2 R_{amp}$$

$$E_i \left(R_c + \frac{2R_{amp} R_a R_d + R_{amp} R_d^2 + 2R_a R_d^2}{2R_{amp} R_a + 2R_{amp} R_d + R_a^2 + R_d^2 + 2R_a R_d} \right)$$

$$= \frac{IR_a R_d^2 R_{amp}}{2R_{amp} R_a + 2R_{amp} R_d + R_a^2 + R_d^2 + 2R_a R_d}$$

$$E_i [R_c + R_g] = K$$

where

$$R_g = \frac{2R_{amp}R_aR_d + R_{amp}R_d^2 + 2R_a^2R_d}{2R_{amp}R_a + 2R_{amp}R_d + R_a^2 + R_d^2 + 2R_aR_d}$$

$$K = \frac{IR_aR_d^2R_{amp}}{2R_{amp}R_a + 2R_{amp}R_d + R_a^2 + R_d^2 + 2R_aR_d}$$

APPENDIX H: METHOD FOR EVALUATING R_x

Laboratory Procedure for R_x Measurement

1. For a given type of transducer and a known length of cable (e.g., 4,000 ft) the value of the cable correction factor, F_L, is measured. This is done by applying a known physical input to the transducer and evaluating the calibration resistor equivalent to the physical input in both cases (i.e., with a near-zero length of cable and with the 4,000-ft cable running between the transducer and the signal-conditioning unit). The value of R_g (the transducer constant) is added to the value of the calibration resistor in both cases and F_L is evaluated by the following equation

$$F_L = \frac{R_{c_L} + R_g}{R_{c_o} + R_g} \qquad \text{(H1)}$$

2. In Equation H1 R_{c_L} and R_{c_o} are the calibration resistors equivalent to the physical input applied to the transducer with long and short cables, respectively. This value of F_L is used in the following equation

$$F_L = \left(1 + \frac{2R_L}{R_x}\right)\left(1 + \frac{2R_L}{R_E}\right) \qquad \text{(H2)}$$

to evaluate R_x.

3. In Equation H2 R_L represents the resistive value of the cable, while R_E represents the input resistance of the transducer.

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